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California State Water Project

Volume V Control Facilities

Bulletin Number 200 November 1974

State of California
The Resources Agency
Department of Water Resources

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BULLETIN No. 200

CALIFORNIA STATE WATER PROJECT

Volume V

Control Facilities

November 1974

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Secretary for Resources
The Resources Agency

RONALD REAGAN
Governor
State of California

JOHN R. TEERINK
Director
Department of Water Resources

FOREWORD

This is the fifth of six volumes which record aspects of the planning, financing, design, construction, and operation of the California State Water Project.

The State Water Project conserves and distributes water to much of California's population and irrigated agriculture. It also provides electric power generation, flood control, water quality control, new recreational opportunities, and enhancement of sports fisheries and wildlife habitat.

Construction of the first phase of the State Water Project was completed in 1973. The $2.3 billion reimbursable cost is being repaid by the water users and other beneficiaries. It is expected that another $0.7 billion will be spent during the next decade to construct authorized facilities for full operation.

This volume discusses aspects of the planning, design, construction, and operation of the various control systems associated with the Project. Though the facilities of the Project are varied and located throughout the State of California, they must be operated as a single system and must be coordinated with the operations of other agencies. This operation is carried out through systems which have been integrated projectwide to provide remote monitoring and control of power and pumping plants, dams and reservoirs, aqueduct control structures, and various other hydraulic features throughout the Project. The system represents a sophisticated application of monitoring and control procedures on a scale never before used on water conservation and transportation projects.

The other volumes give the details of the history, design, construction, and operation of the Project. The subjects are: Volume I, History, Planning, and Early Progress; Volume II, Conveyance Facilities; Volume III, Storage Facilities; Volume IV, Power and Pumping Facilities; and Volume VI, Project Supplements.

John R. Teerink

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ABSTRACT

This volume describes the planning, design, construction, and operation activities which occurred during the period of implementing the control system for the State Water Project.

Early system planning indicated that more efficient and reliable methods of control, other than those in existence elsewhere, were necessary for the operation of the State Water Project. This planning also indicated that fully automated control was both economically and operationally justified, and should be considered. A control system plan was conceived to develop the system and implement it concurrent with the placing into operation of the conveyance and storage facilities of the Project.

An important feature of the planning of a control system to operate the State Water Project was the implementation of an Automation Pilot Model on the South Bay Aqueduct. This Model served as a prototype to evaluate various control system configurations and concepts, evaluate the plan of operation, and plan the optimum control system for the State Water Project.

Subsequent to design, but concurrent with construction of the South Bay Aqueduct Control System Model, an Operations Control Plan was developed to define the structure of the projectwide control system and the operational relationships between the individual facilities to be controlled, that is, detailed operating criteria for all features of the Project. These criteria served as the guide for the design of the projectwide control system.

The actual design and construction of the Project Control System took place between 1964 and 1974. All significant portions of the work to construct the control systems for the Project were performed by contractors under the provisions of the State Contract Act.

The communication systems required for the operation of the State Water Project are comprehensive and extensive. These communications have been leased from telephone industries within California. Communication systems are one of the most critical elements in the Project Control System.

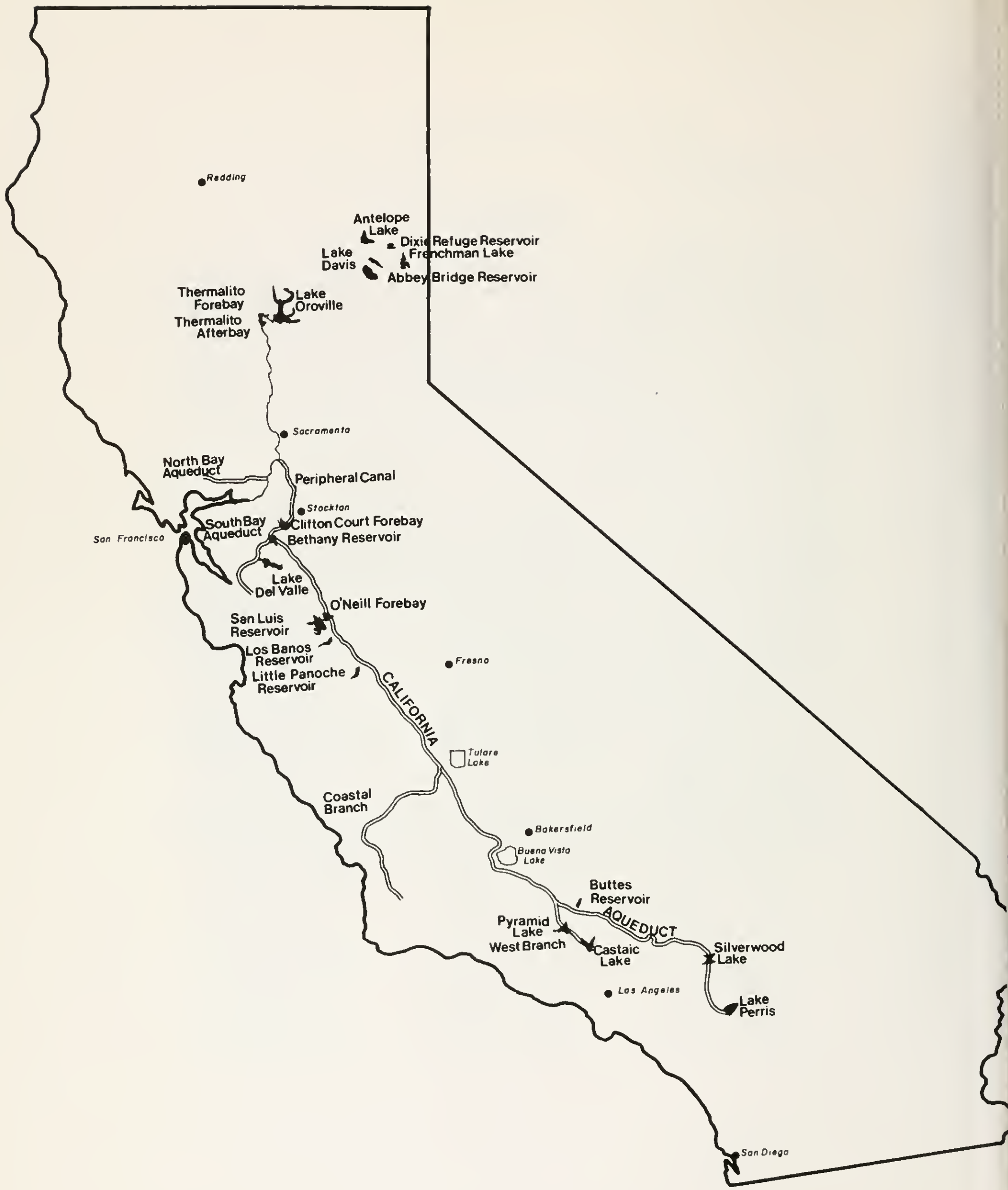


Figure 1. Facilities of the State Water Project

CHAPTER I. INTRODUCTION

Major decisions made early in the planning of the State Water Project dictated the need for a responsive and reliable control and monitoring system. The design of project features and the proposed method of operations ruled out a local manual type of operation used in many other water conservation and transportation projects.

Though the facilities of the Project are varied, and located throughout the State of California, they must be operated as an integrated system and must be coordinated with the operations of other agencies. Figure 1 shows the location of the various features of the Project.

The control system consists of instrumentation, communications, computers, and other electronic equipment to provide for the remote monitoring and control of 17 pumping and power plants with 119 hydroelectric units, 71 check structures with 198 radial gates, and other miscellaneous facilities.

To facilitate the control of these facilities, the Project is divided into five separate control areas: (1) Oroville-Thermalito, (2) Delta, (3) San Luis, (4) San Joaquin, and (5) Southern California. Each area has a control center from which remote control of all facilities within that control area is performed and supervised.

A Project Operations Control Center, located in Sacramento, is responsible for the management and coordination of all operations of the Project. This center also serves as a back-up control center for any of the aqueduct area control centers. This redundancy is essential to provide the high reliability required by the project control systems.

Three basic categories of control systems are provided throughout the Project. They are:

1. Aqueduct Control Systems—Systems which interconnect the Project Operations Control Center and the area control centers with remote sites throughout the Project.
2. Plant Control Systems—Local systems within the plants which provide for local and remote control of specific pumping and power plant functions necessary for operation of the plant.
3. Miscellaneous Control Systems—Systems which provide for remote control and monitoring of other hydraulic features throughout the Project, including spillways, reservoirs, intakes and outlets, and turnouts.

In this volume, the planning, design, construction, and operation of the various control systems are discussed.

This volume is oriented to the noncontrol system engineer or interested public works official who may be faced with a similar need to implement such control systems. To the practicing professional control system engineer or technician, it will serve as an orientation guide to point the direction of the Department of Water Resources' efforts in development of a control system.

CHAPTER II. PLANNING CONSIDERATIONS

During the formulation of the State Water Project, an examination was made of existing operational methods used in other similar projects throughout the United States. It was concluded that more efficient and reliable methods of control than those in existence elsewhere were necessary for the operation of the State Water Project. In addition, process control and systems equipment had advanced considerably and were being continually improved. This made it desirable to evaluate the use of advanced equipment and techniques to control operation of State Water Project facilities.

In 1961, the Department started an investigation of methods of controlling the operation of the State Water Project with particular emphasis on the following items:

1. An investigation of total system requirements.
2. A review of proposals presented by various control systems firms.
3. An investigation of work in this field done by other agencies.
4. A review of the Department's needs, not only for control systems but also for other management and operational needs.

Operational Constraints

Operational concepts and requirements imposed certain constraints on the method of control. There were three requirements which were basic to the proposed method of operating the Project. These requirements were to: (1) meet contractual agreements of water customers by use of the "controlled volume concept" of operation, (2) provide for minimum on-peak operation, and (3) respond immediately to adverse operating conditions or emergencies.

Controlled Volume Concept of Operation

The operational philosophy which was developed to meet water contractual obligations has been designated the "controlled volume operation". This concept of operation permits a rapid change of flow in the canal reaches of the California Aqueduct to be accomplished with a minimum of water surface fluctuation. This concept was dictated by special and unique physical characteristics of the Project.

Controlled volume operation is a concept which utilizes the philosophy of nearly simultaneously operated, projectwide, aqueduct facilities. The water level in the Aqueduct is checked to full design depth at all times. When a change in flow is required, pumping units are started or stopped and check gates raised or lowered simultaneously. As additional pump units are started or stopped, check gates again are raised or lowered simultaneously. By operating the facilities in this manner, flow in the Aqueduct increases or decreases without appreciably changing the volume of water in the canal cross section. This approaches pipeline flow conditions in the open aqueduct.

The main stem of the California Aqueduct is 444 miles in length, of which 391 miles are canal, 12 miles are tunnel, and 41 miles are pressure pipeline. Consequently, water customer service requires special consideration, since it takes a particle of water approximately 15 days to travel that distance, depending on the velocity of flow in the Aqueduct. Controlled volume aqueduct operation provides the capability to make a maximum delivery change rapidly through the Aqueduct.

San Luis Reservoir, O'Neill Forebay, and Silverwood Lake provide the major facilities for regulating the water en route through the main aqueduct. Controlled volume operation minimizes the need for offstream storage, spill basins, or wasteways.

Limitations of water surface fluctuations add to the difficulty of moving water through the Aqueduct. The design of the Aqueduct has placed certain restrictions on its operation with regard to maximum allowable water-level fluctuations. In the canal portions of the Aqueduct, the lining consists of 4-inch-thick unreinforced concrete panels without underdrains. To reduce the risk of lining failure, flow changes in the Aqueduct must be controlled normally within the following criteria:

1. Water surface fluctuations must not exceed 6 inches in one hour or 1 foot in any 24-hour period.
2. If a 6-inch drop is taken in any one hour, the remaining 6 inches must be distributed uniformly over the other 23 hours.
3. The initial 6-inch fluctuation may be taken in less than one hour.

Controlled volume operation reduces the adverse effects of hydraulic transient conditions in the Aqueduct. Water surface fluctuations are reduced to almost half that of the conventional method of aqueduct operation.

Over half of the water delivered through the Aqueduct is for municipal and industrial use, which requires operation throughout the year with delivery of high-quality water and a minimum of outages. A highly efficient year-round delivery capability with minimum manpower costs is necessary.

Certain cross-drainage structures located along the Aqueduct were designed to divert water into the canal during periods of high runoff. This inflow could cause adverse operating conditions. The concept of control had to provide capability to react immediately to correct this condition, thereby keeping damage to a minimum and restoring the operation to normal in minimum time.

Minimum On-Peak Operation

Pumping costs during on-peak power demand hours are considerably higher than similar pumping costs during off-peak hours. For this reason, minimum pumping during on-peak hours was adopted as an operational objective.

On-peak hours are the hours of the day in which demand for power by nonproject users is the greatest. These hours are from 0700 to 2200 hours, Monday through Friday, and from 1300 to 2200 hours on Saturdays.

Pumping operation outside these hours provides the required pumping at the least cost. This pumping scheme places great reliance on the method of control, since flow modifications are greater in magnitude and occur more often within this compressed time period.

Response to Emergencies

Several natural physical characteristics affect the Aqueduct and make it susceptible to damage and failure.

The Aqueduct crosses a number of faults and, throughout most of its length, is in a seismically active area. Failure or rupture of some portions of the Aqueduct at some time is possible. The method of control must have the capability of responding rapidly to isolate the appropriate reach by stopping the flow downstream from the failure and reducing the flow upstream to an amount equal to the water customer deliveries upstream from the failure.

Through the San Joaquin Valley and Antelope Valley, the Aqueduct traverses areas that are bisected by few natural drainage channels of sufficient capacity to carry full flow of the Aqueduct. For wasteways to effectively handle emergency flow from the Aqueduct, it would have been necessary to construct expensive detention basins or excessively long channels to take the water to the San Joaquin River or similar drainage courses. An alternative, and more economical approach, was to include check structures at sufficient spacing to contain the water in the Aqueduct during these emergencies. The use of check structures to create basins in the Aqueduct, in combination with controlled volume operation, provides the capability to perform the function of controlling excess water in the Aqueduct. This is accomplished by rapidly reacting to any adverse operating conditions through the aqueduct control facilities and immediately adjusting the check structures and pumping plants.

Other Control Requirements

In addition to operational constraints, it was determined that the control philosophy for the Project had to satisfy other control requirements. These were:

1. High degree of reliability.
2. Integrated operation of the facilities of the State Water Project.
3. Coordinated operation with associated water and power projects.
4. Centralized dispatching of water and power.
5. Provision for systematic and flexible growth.

Reliability

The method of control adopted for application to the Project had to be inherently reliable. Economic loss would result should a malfunction disturb the operating regimen of the power generation features. In additon, damage and possible loss of life could occur due to malfunction of control features in the open-channel portions of the California Aqueduct, particularly through the highly developed San Joaquin Valley and the densely populated areas in Southern California. Thus, the method of control of the system had to provide a high degree of reliability.

Integrated Operation of Facilities

The following guidelines were established for integrated operation of the facilities. The State Water Project would consist of varied features whose interdependence would be such that completely integrated operation was a requisite.

Oroville-Thermalito complex would be operated for long-term carryover storage as well as power generation. Releases from Oroville would be controlled primarily to meet water demand schedules, power generation, and water quality control in the Sacramento-San Joaquin Delta. Three pump-generation units at Thermalito and Edward Hyatt Powerplants would provide for off-peak pumpback capability to maximize on-peak power generation.

San Luis Reservoir would provide seasonal storage capacity for, and would regulate flows in, the California Aqueduct. Pumping into the Reservoir and releases from it would be integrated with operations to the north and south.

The California Aqueduct would be operated for both water transportation and conservation. The Aqueduct, from San Luis Reservoir to the Tehachapi Mountains, would present a difficult problem in control. Since it would be very expensive to provide spillways, spill basins, or off-canal storage, and since canal storage would be limited by freeboard and allowable water surface fluctuation, close and simultaneous control over several reaches of the Aqueduct would be a necessity.

A succession of pumping plants on the north side of the Tehachapis and power recovery facilities on the southern slopes would require that reactions to a departure from steady state operation in this area be rapid and general in nature. The aqueduct operation as far north as San Luis could be affected.

The complex interrelationship between all project features would preclude any extended operation of one independently of the others.

Coordinated Operation with Associated Projects

Coordinated operation with other water and power agencies would be a requirement for efficient operation and best utilization of resources. Further guidelines were established for this type of operation.

One requirement would be the scheduling and coordination of power generated and consumed by the Project with participating power utilities. The upstream reservoirs of the State Water Project and the Federal Central Valley Project would be operated, insofar as possible, in a coordinated manner. This coordinated operation would provide economic and operational benefits by increasing the firm power yield of the combined generation capabilities through optimization of water releases to satisfy water demands of service areas and power demands at load centers.

Further coordination would be required between the State Water Project and the Federal Central Valley Project through operation of the San Luis Joint-Use Facilities. The Department would operate these joint-use facilities to serve water to both federal and state service areas upon a predetermined water delivery schedule.

Centralized Dispatching

In accordance with the basic requirements previously stated, a centralized point of monitoring and dispatching of overall project operation would be necessary. This project control central would serve to coordinate the operation of all of the facilities of the entire Project. Scheduling and dispatching information would be transmitted to the control central from the operating facilities of the integrated systems. These data would be analyzed and reduced to provide optimum control and operation of the facilities.

The control central would receive requested water delivery schedules for state service areas as well as a schedule from the U. S. Bureau of Reclamation for deliveries to federal service areas.

In addition, operational data concerning upstream storage and power generation capabilities would be transmitted into this control central. Participating power utilities would receive power schedules for project pumping and transmit schedules for project power generation to and from this facility.

Provisions for Expansion

The growth and development of California and the long operating life of the State Water Project made it imperative that provision for systematic and orderly expansion of control be a consideration in adoption of any control method. As operating experience was gained and changes in operational concepts became necessary, the method and equipment employed for control would have to be flexible and adaptive.

With these guidelines in mind, the Department embarked on an investigation of various control concepts which could be employed for the State Water Project.

Control Concepts

Five control concepts were investigated within the operational constraints and control requirements. These five concepts were:

Manual Control
Conventional Control
Remote Control
Semiautomated Control
Fully Automated Control

To compare these concepts on a common basis, each was defined and its application to the Project for both normal and emergency operation was described.

It was assumed that the system or process pertained only to State Water Project facilities. All functions which would be conducted at departmental headquarters, such as contractor billing and accounting for water and power, were excluded from these descriptions. In all cases, it was assumed that adequate mobile radio communication capabilities existed.

Manual Control

Manual control was defined as direct on-site control and supervision of all features in the system. Operators would make the physical control manipulations at the sites required to achieve the operational objectives.

Operators would be required to read staff gauges, manipulate the release mechanisms, and measure and read the released flow rates at the reservoirs throughout the system. As the operator performed these duties, he would log his actions.

The operator assigned to generating plants would be required to operate and monitor each unit from the unit control boards. In the case of pumping plants, relatively the same conditions would apply.

In the open-channel portions of the Project, water operators (ditch riders) would be required to regulate aqueduct checks and maintain correct flow rates through service area turnouts. The operators would be responsible for operating up to 40 miles of canal involving such duties as raising and lowering the check gates to maintain a near-constant water surface, reading and logging the values on staff gauges, and measuring and setting the flow rate in the canal. In addition, they would be responsible for setting turnouts to deliver the required flow at each turnout in his area of responsibility. They would be responsible for maintaining and servicing the on-site rcording devices, the records from which would be sent to department headquarters for billing computations.

Manual control would require a large number of operators throughout the system. These operators, in order to achieve a degree of efficient operation, would require considerable training. However, it was foreseeable that a number of these trained operators would be required for normal operation only. Consequently, should an emergency condition arise, some control reactions would be directed by untrained or unfamiliar personnel who normally would have been assigned other duties. It was apparent that the factor of each individual operator's unique reaction to a system emergency could cause unreliable operation.

The application of the concept of manual operation to emergency situations would require that a written set of instructions be supplied to all operators for use in emergencies. These instructions would attempt to eliminate operational errors in the system.

Should an emergency condition arise in the canal, the situation could conceivably go unnoticed for a long period of time. Once the emergency became evident, the reaction time or the time required for the water operators to effect control actions could be lengthy.

Conventional Control

Conventional control was defined as that method which utilized intervening supervisory equipment between the operator and the device to be controlled. For example, within a project pumping or generating plant, conventional supervisory equipment would allow the plant operator to automatically start or stop units from a control room within the plant. The supervisory equipment would sequentially check permissive points, start the auxiliaries, and start the unit. In addition to start-up and shutdown operation, the supervisory equipment would also monitor conditions during operation. These monitored quantities would be displayed on a control panel located in the control room of the plant.

Conventional control of the checks and turnouts in the open-channel portions of the Project would utilize controllers to provide local automatic control. The operator would insert a water level setpoint into this controlling device, which would then control the structure about this setpoint for an indefinite period.

Reservoir water surface elevation readings and gate controls would be reported electronically to a reservoir control center commonly included in the generating plant control room. These readings would be made by floats or other water surface measuring devices equipped with telemetering units. Gate controls would be arranged to allow for remote operation.

Conventional control would be coordinated through area control centers. These area control centers would have radio contact with water operators in the field, as well as radio or telephone contact with pumping plant operators. At these area control centers, system dispatching and data logging would be accomplished by manual means after reception of the daily master schedule from the control central located at department headquarters.

In emergency situations, the conventional supervisory equipment would function to protect the pumping and/or generating units from malfunction. However, should the supervisory equipment itself malfunction, the plant operator would take complete and direct manual control of each unit. Since these failures should occur infrequently, the system would be operating with, at best, unfamiliar if not untrained personnel in emergency situations.

In the open-channel portions of the system, since no indications would be telemetered to a common location, should an emergency condition arise, the time lapse between the occurrence of an emergency and its detection could be great. Once the emergency condition became apparent, the required travel time of the water operator to correct the situation would extend this period.

Should a power failure occur at a pump turnout, the resultant rejected flow would tend to raise the water surface at the checks. As the water surface rose, the local automatic control device at the check would increase the check opening to maintain a constant water surface upstream from the check. As the check opened, the flow through it would increase. Rejected flows would proceed downstream until the capacity of the canal was no longer able to contain them, at which time they would overflow the canal.

The same condition would exist at a gravity turnout; that is, if there were to be a malfunction, the device itself would be unable to indicate such a malfunction to the water operator or apply temporary corrective measures. Therefore, it was apparent that warnings of turnout malfunctions might come from sources other than the project operation staff.

Remote Control

Remote control was defined as that method which utilized conventional supervisory equipment in pumping or generating plants, and terminal equipment and local automatic control devices in the open-channel portions of the Aqueduct which could be controlled from a remote location. That is, pumping and generating plants would be controlled through the use of conventional supervisory equipment which would provide for control from a remote common operation center. The facilities on the canal would be controlled by an operator located at the same control center using either radio or land-line communications to transmit and receive control instruction and information.

As discussed in the section on conventional control, upstream reservoirs would be controlled remotely from the generating plant control room. Water surface indication, gate positions, and quantities of flow would be displayed in the control room for use by the operator. The generating plant would be controlled by operators using conventional supervisory equipment.

In the case of pumping plants, some plants would be controlled remotely from other plants using conventional supervisory equipment with indications and control instructions being received and transmitted via either radio or land-line communications.

Remote control of the canal would require equipment at checks and turnouts which would respond to remotely transmitted signals. This equipment would have the capability of recognizing a coded message containing an instruction, converting that instruction into an action by the control device, and retransmitting back to the initiating location confirmation that the coded message was received and that action had been taken.

With remote control, the ability to react to emergency situations would be greatly enhanced over that of the methods previously discussed. Indications of generating or pumping unit status would be immediately available at all times in the control room. Should the indicators show that an emergency situation was impending, the particular troubled unit could be shut down and a maintenance man dispatched before the actual trouble occurred.

In the canal, it would be possible to foresee an impending emergency condition through the use of remote indication. In an emergency, such as a power outage at a pump turnout, the condition of this pump would be remotely indicated at the control center and would therefore provide instantaneous notification of its outage to the water operator. The operator would then be able to cope with the rejected turnout flow by the regulation of checks up- and downstream from the outage area.

In case of a failure of on-site or terminal equipment, which would receive and transmit messages to and from the control center, the operator would receive an instantaneous indication. A technician would still have to be dispatched, however, to repair the equipment item that failed, thus resulting in a comparable travel time to that mentioned in the previous discussions.

Semiautomated Control

Semiautomated control of the State Water Project would utilize the capabilities of a process control computer or processor to effect control of upstream storage reservoirs, generating plants, and pumping plants in the system and to receive data from on-site sensors in the open-channel portions of the California Aqueduct to provide guidance for the operator in the control center.

In the operation of upstream reservoirs and generating plants, the control processor having responsibility for that particular facility would accomplish the required scheduling within a master schedule as transmitted from a control center and would release the required flows from the storage reservoirs for generation. The control processor would also function through conventional supervisory equipment to schedule and operate the pumping plants located throughout the system.

Open-channel portions of the California Aqueduct would be controlled by an operator receiving guidance from a programmed control processor. The processor would receive data from the sensing devices at the control structures in the aqueduct system and would make these data available for use by the operator. All ultimate control responsibility would be placed in the hands of the operator, however.

The concept of semiautomated control would provide for emergency conditions in the system. The processor would receive indications from the conventional supervisory equipment located at generating and pumping plants. These indications would provide for an analysis by the processor and would be followed by a diagnosis of the impending emergency condition. By utilization of the processor's capability to schedule the pumping units, not only for operation but maintenance purposes as well, it was conceivable that emergency conditions would not occur as frequently as under the previously discussed concepts of control.

Fully Automated Control

Fully automated control would involve the introduction of closed-loop, real-time control computers or processors as controlling devices into all control loops required for optimum operation of the State Water Project. The extent to which operators would enter into actual control of these facilities would be limited even in extreme emergency cases. The control system structure was assumed to be a large control central located in Sacramento supervising the functions of five area control centers located in Oroville, near the Delta Pumping Plant, at the San Luis complex, near Bakersfield, and in Southern California.

These area control centers would supervise the operation of that portion of the system under their jurisdiction. An operator would be on duty at these area control centers at all times as would operators (water and power dispatchers) at the control central in Sacramento.

Scheduling and optimizing of pumping and generating plants would be directly accomplished by computers or processors. These processors would function within parameters and master schedules transmitted to them by the control central in Sacramento. Operation of pumping and generating plants would be through the use of conventional supervisory equipment, with monitoring of supervisory indicators done by the processors. The actual hourly generation quantities would be those defined by the participating public utilities in the dispatching schedule coordinated through the control central. Power consumption would be handled in a like manner for the system pumping plants.

In the open-channel portions of the system, during normal operation, radial gate checks would utilize local automatic control about limits or setpoints within schedules as determined by the area processors. These schedules would be determined from the master schedule transmitted to the area control center from control central. The area control center processor, however, would have an override option enabling it to assume control should the local loop device malfunction.

Real-time data from the system would be examined, processed, and analyzed; any system deviations noted; commands issued to correct those deviations and prevent future occurrences; and data logged for storage to constitute essential project records.

Analysis and Comparison of Costs

Each of the five control concepts were rated as to expected levels of performance in specific areas. Table 1 shows the relative standings with a maximum weight of 5 and a minimum of 1. The column totals indicate the overall level of performance which could be expected of each operational concept relative to the others.

Table 1. Relative Expected Levels of Performance of Various Control Concepts

PERFORMANCE AREA	CONTROL CONCEPT				
	Manual	Conventional	Remote	Automated Semi	Automated Fully
Reliability	1	2	4	5	5
Reaction Speed	1	2	4	4	5
Optimum Operation	1	2	3	4	5
Extent of Immediate Control	1	2	4	4	5
Accuracy	1	2	3	4	5
Customer Service	1	2	4	4	5
Warning of Emergency	1	2	5	5	5
TOTAL	7	14	27	30	35

An economic comparison was also made. However, since a comparison of each individual control concept would present difficulties in the accuracy of assessment and assignment of costs, a comparison was made based only on two concepts, conventional and fully automated control (Table 2).

The costs for conventional control were used as base costs, that is, costs for terminal and other equipment which would be used for fully automated control were considered to be incremental. The personnel requirements for conventional control also were utilized as base requirements. The estimated equipment costs were based on proposals submitted to the Department by control systems firms. Costs were included for communication lines from the Sacramento control central to each area control center and from each area control center to the features requiring control. This communication and data gathering system was composed of both land-line and microwave links. The costs as shown did not reflect any use of the existing State of California integrated microwave system but, instead, were based on a completely separate system.

Savings were estimated on the basis of the number of operating positions which would not have to be filled throughout the system. These savings consisted only of salaries and wages and did not include the costs of recruitment and training of personnel for these positions. The costs included a phasing concept which allowed for sufficient staffing at each area control center to allow portions of the Project to become operational in an orderly manner as construction was completed. Once operational, it was assumed that some personnel remained with that portion while the bulk of the staff moved to a succeeding portion. This phasing operation was assumed to last for a period of three years for each completed portion.

This comparison showed that the salary savings derived would be adequate to repay the costs of installing automation equipment. In 1962, when this estimate was made, the present worth of the direct incremental capital costs for automation equipment at 4% interest was estimated to be \$7,094,191. The present worth of costs for maintenance and replacement of this equipment, extended over a 50-year payout period at 4% interest, totaled \$6,388,126.

Savings derived from decreased personnel requirements for fully automated control, compared to the conventional control computed on the same basis, totaled \$26,380,943.

The benefit/cost ratio was:

$$\frac{\text{Total Savings}}{\text{Total Costs}} = \frac{\$26{,}380{,}943}{\$6{,}388{,}126 + \$7{,}094{,}191} = \frac{\$26{,}380{,}943}{\$13{,}482{,}317} = 1.957$$

Factors included in deriving the aforementioned costs were as follows:

Costs of Conventional Control

It was assumed that the total system was staffed with personnel to accomplish required activities in the following categories:

- General Maintenance Unit
  - Plant Maintenance
  - Canal Maintenance
  - Ground and Reservoir Maintenance
- Operations Unit
  - Plant Operation
  - Canal Operation
- Administrative Unit

Costs for personnel in the above categories included the following:

- Personnel Salaries
- Equipment
- Supplies, Materiels, and Tools
- Administrative and General Expenses

Costs of Fully Automated Control

Equipment costs for a fully automated system were derived from several itemized quotations received from equipment suppliers and included substantial allowances for installation, programming, and systems engineering, as well as system hardware.

It was assumed that yearly maintenance costs would approximate 5% of the initial equipment costs. In addition, an equipment replacement allowance was included plus an allowance for software. This replacement allowance was included in the form of a sinking fund of 25-year life at 4% interest. Table 2 summarizes the comparison of cost between fully automated and conventional operation of the Project.

Conclusions and Recommendations on Control Concepts

It was concluded from the analysis that fully automated control of the State Water Project was both economically and operationally justified.

Another conclusion was that this ultimate control concept be phased as the features of the State Water Project were constructed. The decision was made that as each facility was constructed, that facility would initially be operated by either conventional or by remote methods. As experience was gained with remote control, groups of facilities would be phased gradually into semiautomated, and then into fully automated, control.

The following program was adopted in 1962 for the design and implementation of a control system for the State Water Project. This program was divided into four phases:

- Phase 1. Automation Pilot Model
- Phase 2. Preliminary System Design and Performance Specifications
- Phase 3. Final System Design and Procurement Specifications
- Phase 4. Equipment Procurement and System Implementation

Phase 1. Automation Pilot Model

An important feature of the entire analysis made to select a control system to operate the State Water Project was the implementation of an Automation Pilot Model on the South Bay Aqueduct. This Model would serve as a tool to evaluate various control system configurations and concepts, evaluate the plan of operation, and plan the optimum control system for the State Water Project. The Model would function under actual operating conditions on a real-time basis, illustrating the concepts of centralized control.

A consulting engineering firm would be retained to assist with the development, testing, and evaluation of the Model.

The consultants would determine what organizational requirements within the Department would be necessary to successfully engage in the various phases of automation. Also, maximum and minimum participation by the Department would be set forth.

Phase 2. Preliminary System Design and Performance Specifications

A systems engineering firm qualified in the fields of civil engineering, computers, and control systems, but without any product line, would be selected for the purpose of assisting the Department with the work required under Phase 2 of the program. The consultant would supply the necessary engineering services, materials, resources, and facilities to conduct engineering investigations and to design and establish the preliminary system for the control system of the State Water Project. This would be done in accordance with operational criteria furnished by the Department.

In addition, performance specifications would be prepared and furnished for each major item of equipment required in the total system design. The performance specifications were to express requirements in the form of input, output, function, and operational characteristics of items of equipment required to satisfy the system design, leaving the details of design, fabrication, and internal functions of the equipment to the discretion of the Department.

The data processing and control system covered by these specifications would include all data handling

Table 2. Comparison of Costs Between Fully Automated and Conventional Control

Area Control Center	Present Worth of Annual Savings (1)	Present Worth of Cost for Additional Equipment* (2)	Present Worth of Costs for Maintenance and Replacement of Additional Equipment (3)	Total Present Worth of Additional Costs (2) + (3) (4)
Oroville	$3,641,687	$707,037	$640,914	$1,347,951
Sacramento	4,411,868	1,364,198	1,231,397	2,595,595
Delta	2,739,019	1,012,152	921,782	1,933,934
San Luis	3,033,255	1,127,709	1,023,798	2,151,507
San Joaquin	8,387,214	1,794,683	1,594,212	3,388,895
Southern California	4,167,900	1,088,412	976,023	2,064,435
Total	$26,380,943	$7,094,191	$6,388,126	$13,482,317

* Costs of equipment over and above that required for conventional control.

equipment from the source of output of the various turnouts and/or distribution points, the monitoring of certain equipment functions, data assessment and evaluation, recording, computing, and reporting and display to operation personnel for both real-time and deferred-time modes of operation.

Part of the design considerations would include communication requirements for data transmission and control, in accordance with system design requirements.

A complete set of functional specifications and an operational schematic of the total control system would be furnished under this phase of the work.

Phase 3. Final System Design and Procurement Specifications

The Phase 2 consultant would be retained to assist the Department in developing the final system design and procurement specifications for the control system of the State Water Project, if the consultant's performance had been satisfactory under Phase 2 of the proposed program.

The Phase 3 consultant would assist in performing engineering services and supplying materials, resources, and facilities necessary to develop the final system design. It was expected that work performed under Phase 3 might suggest or impose additional design changes or modifications of the Phase 2 design effort. Such changes or modifications to the preliminary design developed under Phase 2, as deemed necessary and as approved by the Department, would be performed as part of the work under Phase 3.

With the assistance of the consultant, procurement specifications, design drawings, and acceptance test procedures adequate for the Department to initiate procurement of the total control system for the State Water Project would be prepared.

In addition to developing procurement specifications of all equipment within the control system, cost estimates would be prepared for the equipment required.

Implementation schedules would be formulated and would consider all equipment, systems, and facilities necessary to implement the overall control system of the State Water Project. Each implementation step would increase the overall capability of the system. In no case would an implementation step decrease the capability of the system. The implementation schedule would not be tied to calendar dates but would establish sequential steps of implementation by consideration of such factors as cost estimates for each step, importance and priority of various portions of the automated system, optimum efficiency of implementation, and least interference with the daily operation of the State Water Project. Most desirable grouping of implementation steps and optimum time breaks would be indicated.

Phase 4. Equipment Procurement and System Implementation

This phase of the program would be accomplished in accordance with the implementation plan developed under Phase 3 and would be accomplished under a number of procurement contracts. The number and scope of the contracts would be dependent upon the various systems or subsystems to be installed at a given time in accordance with the implementation plan.

It was conceivable that one contract might be awarded to install one portion of the system located at the northern section of the State Water Project, two or three contracts covering the southern portion of the Project, and miscellaneous contracts for other portions of the system. Where desirable, one contract would be awarded to furnish complete major systems encompassing a number of subsystems. However, due to the long time period involved in the final implementation of the Project, it was not considered desirable that one contract be awarded for the total system.

The Department and the consultant would monitor the manufacturer to assure that specifications developed under Phase 3 were adhered to.

As discussed in subsequent chapters, the four-phase program for the design and implementation of the control system for the State Water Project was modified; only Phase 1— Automation Pilot Model— was followed essentially as proposed.

CHAPTER III. SOUTH BAY AQUEDUCT CONTROL SYSTEM MODEL

Phase 1 of the program to develop the design and implementation of the control system for the State Water Project was the Automation Pilot Model. Initially, the "Model" was to have been installed only on the facilities of the South Bay Aqueduct, extending from South Bay Pumping Plant through Patterson Reservoir. This was later expanded to include all facilities of the South Bay Aqueduct.

The information gained from the test and evaluation of the Model was to have been used by the Department to proceed with design and construction of the remainder of the project control system in accordance with Phases 2, 3, and 4 previously described.

Objectives of the Model

The broad objectives of the South Bay Aqueduct Control System Model were twofold:

1. Provide an adequate means to remotely control and monitor the South Bay Aqueduct from a control center; and

2. Provide experience in the design, procurement, installation, and operation of a system having the capability to be used on the entire aqueduct system.

Since the requirements for remote control of a small aqueduct, such as South Bay, were minor compared to the requirements for a large aqueduct, it was evident that a system fulfilling the second objective would more than fulfill the first.

Thus, the major design effort was applied to the objective of reproducing on a smaller scale a control system, the concept of which could ultimately be expanded to control the entire California Aqueduct.

To be a suitable model and to produce the information desired, certain representative subordinate objectives were established. Among these were:

1. The number of controlled sites and number of functions at each site would have to be large enough to make the results applicable to a more extensive system.

2. The variety of functions and types of controlled sites would have to be representative of future requirements.

3. The system would have to be computer compatible to enable the testing of various concepts of "operator guide" operation using a computer in a control center in Sacramento.

4. Communications would have to be designed for high reliability and efficient use, and experience gained would likewise have to be transferable to the larger system.

An additional objective of the system was to provide benefits to the Department in the way of enhancing its capability to design, construct, operate, and maintain a sophisticated control system. A detailed list of these anticipated benefits was prepared before construction of the Control System Model was begun.

Design Objectives

1. Evaluate specifications as to conformance and adequacy.
2. Make model specifications and other pertinent data available to designers.
3. Enhance experience of control system designers.
4. Establish design criteria.
5. Evaluate equipment under environmental conditions.

Construction Objectives

1. Enhance quality control capability.
2. Enhance experience of resident engineers in installation techniques.
3. Improve acceptance testing and check out experience.

Operations and Maintenance Objectives

1. Evaluate control techniques for operation.
2. Simulate operational control system problems or malfunctions.
3. Determine optimum application of computer control in operation.
4. Provide trained experienced personnel for California Aqueduct operations activation.
5. Provide operator and maintenance training programs.
6. Determine human factors—man-machine interface relationships.
7. Evaluate maintenance concepts.
8. Develop emergency control procedures.
9. Develop safety procedures.
10. Develop test control procedures for normal operation, component failure, equipment maintenance, or other critical situations.
11. Evaluate use of computer as an off-line device.
12. Establish water and power dispatching procedures.
13. Establish data logging and customer billing procedures.
14. Determine the number and classifications of personnel required in area control centers and Sacramento control center.

Consultant Participation

One of the first steps in the Control System Model Program was to retain a consulting firm to assist the Department in planning, designing, constructing, testing, and evaluating the Model. In 1962, the Department required additional technical expertise in the area of computerized control systems, and it was believed that use of a consultant to enhance this expertise was imperative.

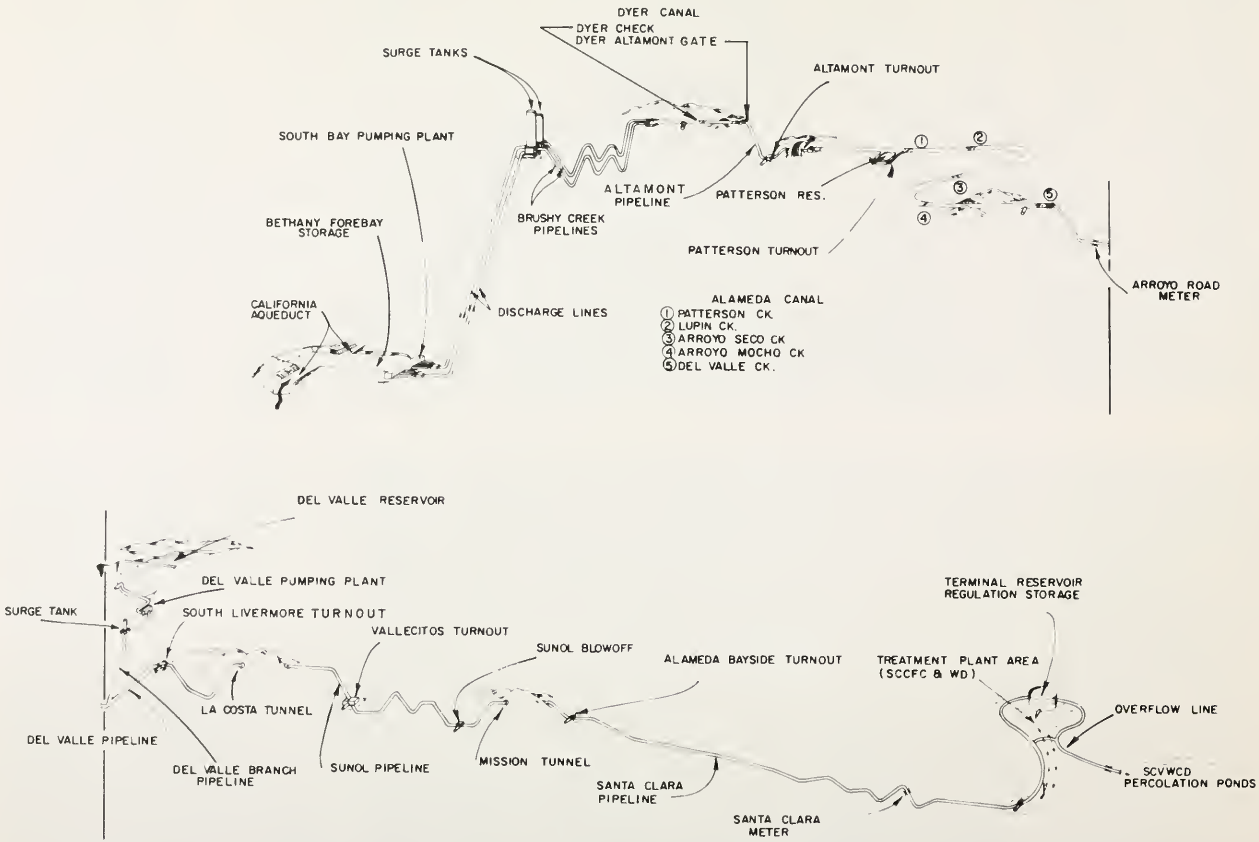


Figure 2. Facilities of the South Bay Aqueduct

At about the same time, digital control systems using transistor electronics had been developed for military and space systems but had not yet been widely applied in industry. The Department's engineering personnel involved in the development of the proposed control system generally came from an industrial background.

These factors made it advantageous to seek the advice of a consultant in determining the best choice of methods to supply the required monitoring and control capabilities.

Selection of a consulting firm was made on the basis of experience in control systems similar or applicable to the one proposed. Other factors considered were the willingness to work directly with department engineers rather than independently and the understanding that the firm would not be involved as contractor in any phase of system implementation. The firm of Daniel, Mann, Johnson, and Mendenhall of Los Angeles, California, was engaged in January 1963.

Scope of the South Bay Model

The South Bay Aqueduct branches from the California Aqueduct approximately 2 miles downstream from the Delta Pumping Plant. At this point, the South Bay Pumping Plant lifts the diverted water 545 feet to the top of an adjacent hill from which the Aqueduct extends 42 miles through hill and valley terrain to a terminus near San Jose. This Aqueduct with 300 second-foot capacity consists of 32 miles of pipeline, 8 miles of open concrete-lined canal, and 2 miles of tunnel. Figure 2 schematically shows the facilities of the South Bay Aqueduct.

The South Bay Aqueduct Control System Model, as installed, provided complete control and supervisory capability from two locations of 17 separate facilities of the South Bay Aqueduct, i.e., 1 pumping plant, 7 check structures, 3 turnouts, 2 water quantity measuring meters, 1 blowoff valve, 1 terminal storage tank, and 2 reservoirs. These facilities can be controlled from either of two control centers, one located at the Delta Pumping Plant and the other located in Sacramento.

The Control System Model was originally developed for installation on the South Bay Aqueduct between South Bay Pumping Plant and Patterson Reservoir. This concept included analog-to-digital conversion at the South Bay Pumping Plant, digital data transmission between there and Sacramento, and a control center at Sacramento with a computer installed at that facility.

In April 1963, a decision was made to extend the Model through the Vallecitos Turnout of the South Bay Aqueduct in order to provide a reach of aqueduct with five check structures in series to test operational concepts. The Model was extended to the Santa Clara Terminal in March 1963 to ease the operational problems and to facilitate water deliveries.

The implementation plan called for development of the Model in four stages as follows:

- Stage 1—South Bay Aqueduct System including the South Bay Control Center.
- Stage 2—Sacramento Control Center.
- Stage 3—Communication facilities between the South Bay and Sacramento Control Centers.
- Stage 4—Real-Time Computer System at Sacramento.

The early stages of design activity were devoted to development of criteria and functional requirements of the control system. These criteria and requirements are summarized in Reference 1 (See Appendix A for references).

An important decision was made in early 1965 to make use of leased telephone facilities for communication rather than to build a department-owned and operated facility. The reasons for this decision and the details of the system leased from the telephone company are discussed in Chapter VII, "Communication Systems."

South Bay Aqueduct Control System (Stage 1)

Design of the South Bay Aqueduct Control System

The equipment required for control of the Aqueduct from the South Bay Control Center was divided into the following general subsystems:

Site Equipment Subsystem
Communications Equipment Subsystem
Control Center Subsystem

There were also other items of construction incidental to the control system. Figure 3 shows a functional block diagram of the South Bay Aqueduct Control System.

Site Equipment Subsystem. At each of the 17 sites, the conventional switches to turn motors on and off, the transducers to measure motion and position, and automatic setpoints and alarms to set and measure limits of movement were specified for installation on the equipment to be controlled or to be monitored. These devices are connected by cables to the control equipment which is located in a small adjacent building. The equipment rack in this building contains:

1. A digital logic package to decode and validate incoming messages and to encode outgoing messages, to set up proper switching, to maintain alarm surveillance, and to convert any analog signals into digital form.
2. Electronic comparators and setpoint units to provide automatic control.
3. Transmitters and receivers for the communication phase.
4. A local control panel to allow personnel visiting the site to have local-manual control.

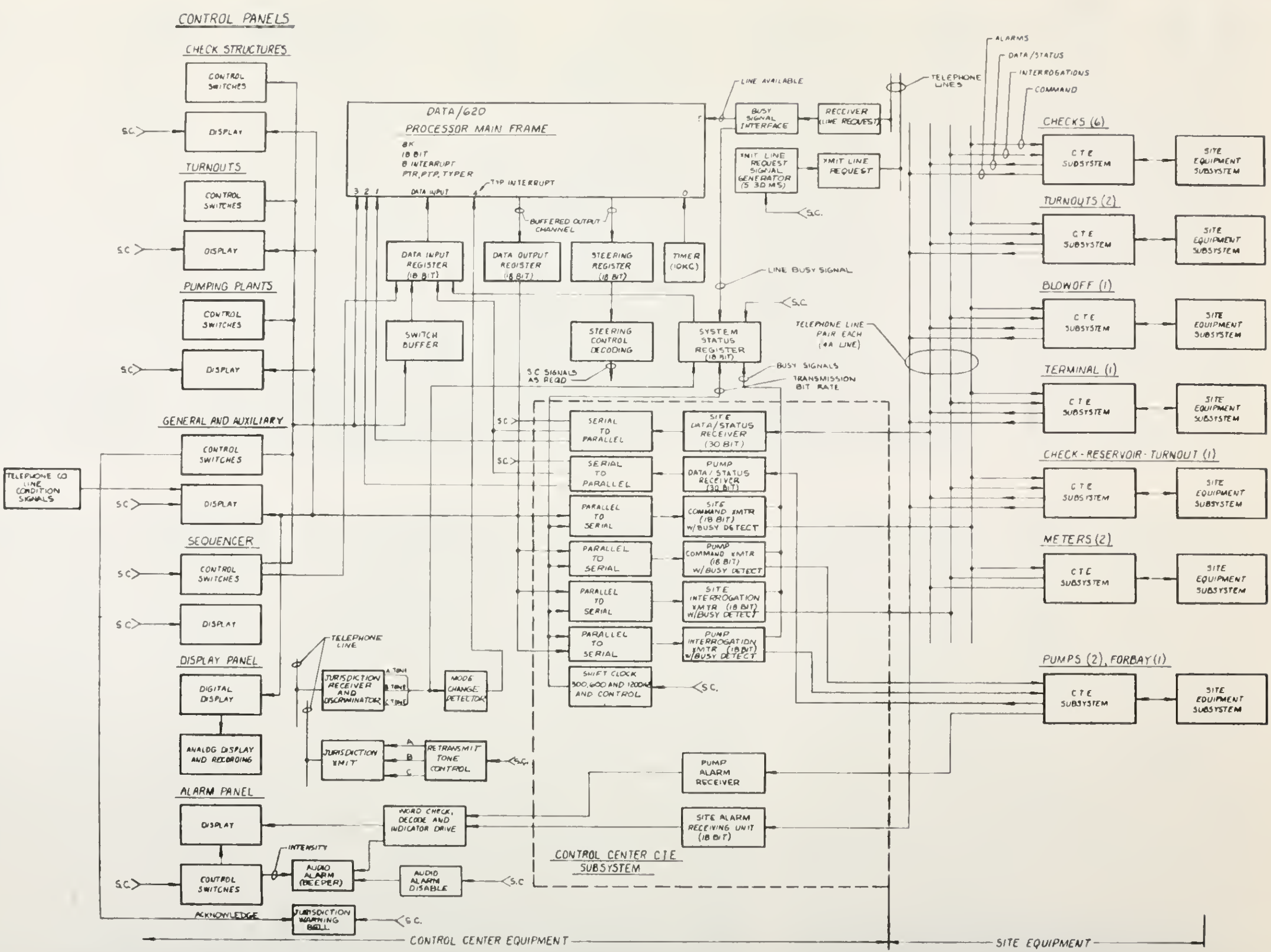


Figure 3. Functionol Block Diagram—South Bay Aqueduct Control System

Gray-code encoders are widely used on the system. Their ability to directly encode angular position made them ideal for gate-position and water-level measurements. They were also adopted as a means of encoding the rotary motion of pulse-duration transmitters which had already been installed for pressure and water flow rate telemetering.

Design called for use of both brush and optical encoders so that both could be tried. Brush-type encoders were specified where attached to the telemetering instruments because of their low torque requirement and high resolution for small angular travel. The optical encoders were generally less satisfactory, principally because of lamp failures.

Gate-position measurement is accomplished by use of a tape and take-up reel driving a digital encoder. This method is capable of measuring gate position to an accuracy of $\pm$ 0.05 foot for gates having a range of travel of up to 6 feet. On the larger gates of the main aqueduct, which have 30 feet of travel, this method does not have sufficient accuracy even when the accuracy requirement is reduced to $\pm$ 0.1 foot. As a result, a different method of measuring gate position was devised for use on the main aqueduct (see Chapter V, "Control System Design").

Local, automatic, water-level controllers were also specified for the check structures. These controllers compare the actual water level at the check with a desired water level setpoint and, when placed in control of the gate, operate the gate in the direction required to bring the water level to the setpoint. The location of the controlling setpoint is selectable between positions upstream and downstream of the check gate. The comparator also provides an alarm when the level deviates from the setpoint by an unacceptable amount.

The controllers have two different principles of control. One type uses a percentage timer principle in which the gate is run in the correcting direction for a selected percent of the time that the water level error existed (a "bang-bang" controller). The other type uses a "proportional-plus-reset" principle in which the amount of gate movement is determined by adding together one correction proportional to the amount of error in water level and a second correction proportional to the time (interval) of the water level error.

These local controllers were tested in the Model to determine if they would be useful as standby controls when failures made it impossible to exercise remote control or monitoring.

Site equipment was initially installed in prefabricated sheet steel buildings. These buildings proved unsatisfactory because the environment within them caused the equipment to fail prematurely. It was eventually necessary to insulate the buildings and add air conditioning in order to keep the equipment at a suitable operating temperature. Figure 4 shows a typical site layout.

Communications Equipment Subsystem. Design specified the digital word used for communication between the control centers and the sites and the coding of information contained within the word. The data rate is selectable at 300, 600, and 1,000 bits per second. Although 1,000 bits per second (bps) was desired, there was some concern that communication errors might be excessive at such a high rate. Testing of the various data rates indicated that the 1,000 bps rate was entirely satisfactory, and the lower rates have never been used. There are four separate types of communication words: command, interrogation, data-status, and alarm. Each of these is sent on an independent communication channel. Commands, interrogations, and alarms are 18-bit words with only 6 bits of "function identification", while the data-status word has 30 bits and includes a 13-bit space

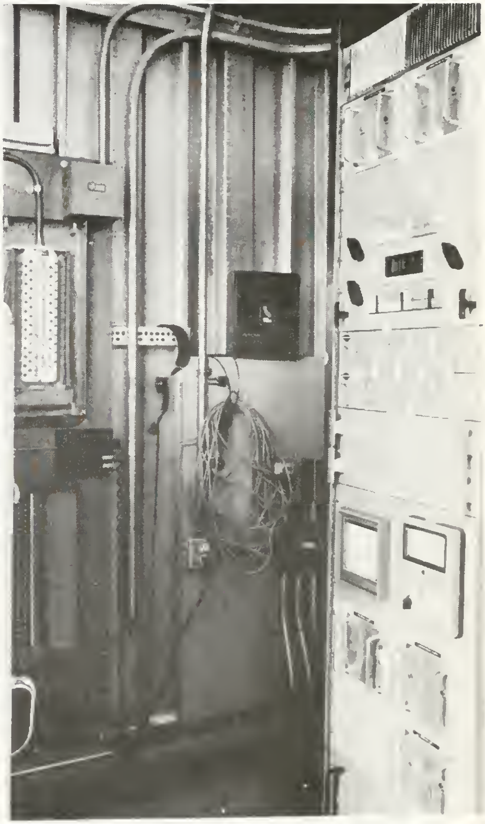


Figure 4. Typical Site Layout—South Bay Aqueduct

for numerical values. A single parity bit and 5-bit "Start of Message" code is used for security. Gate positions, water levels, and other quantized data are received at the control center, but setpoints cannot be transmitted to the site. This requires continuous interrogation from the control center when changing the position of gates or valves in order to know when the desired position is reached and the control action stopped.

Alarms are transmitted spontaneously when the event occurs. This requires a rather elaborate communication line-checking procedure to avoid placing more than one alarm word on the line simultaneously.

Control Center Subsystem. The control console at the South Bay Control Center provides the operator with the capability to control and monitor the 17 sites individually by means of four control panels and to monitor alarms on an alarm panel. Pumping plants, checks, and turnouts are each controlled from an individual panel while the remaining facilities are grouped and controlled from the fourth panel. Alarms from all facilities are annunciated on an alarm panel. Figure 5 shows the control center equipment.

By selecting a particular site to be shown on the appropriate panel, the operator can change operating conditions at that site and/or obtain data or status from that site. The console also contains an automatic sequencer that allows the operator to set up simultaneous and automatic changes such as gate position or valve position through setpoint control. In other words, the operator can set up an arrangement whereby a number of gates or valves are automatically positioned to a preset value.

A digital display panel at the control center displays pertinent data items to allow the operator to continuously ascertain current conditions. This panel is automatically updated about once a minute.

There also is an analog meter panel which displays some of the data, such as gate positions and water levels. These same data are also displayed on the digital display panel. The analog and digital displays are shown in Figure 6.

Two, 2-pen chart recorders, which may be selected to record any of the analog data, are provided. The strip-chart recorders are activated by manual switching.

At the heart of the South Bay Control Center is a small computer system. When the contract for this system was being awarded, the "mini-computer" was just beginning to change the industrial control system picture. Before that time, the switching and logic functions required for supervisory control, data logging, and data display were obtained by elaborate

Figure 5. South Bay Control Center

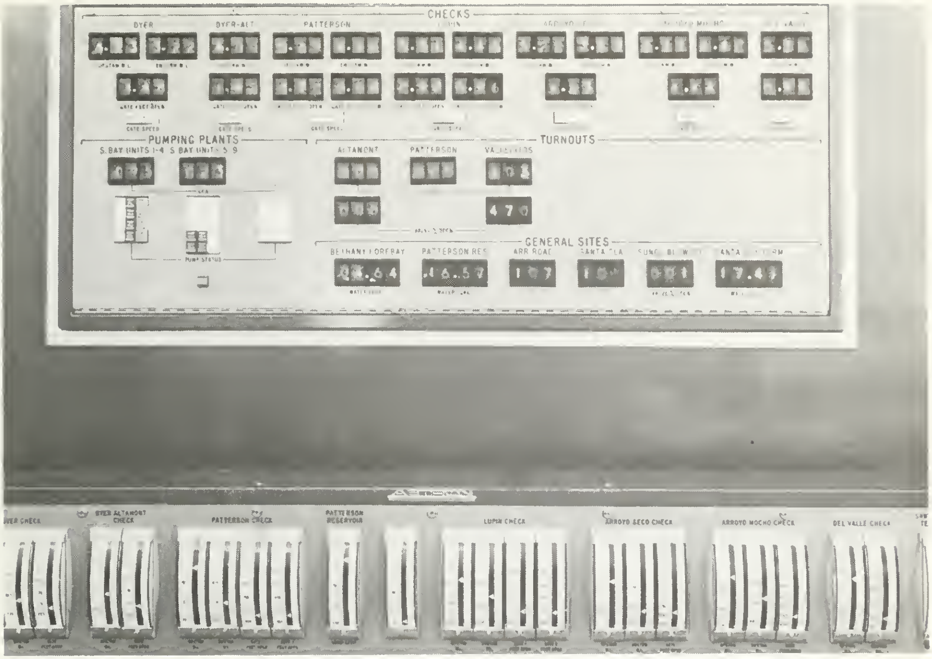


Figure 6. Analog and Digital Display Panel—South Bay Control Center

wired-logic systems. With the availability of programmable devices at competitive cost, the use of mini-computers became attractive.

Although the South Bay Model was specified as a "hard-wire" system, that is, not using a computer, a qualification was added to the specification permitting the use of a "processor" for the control consoles and display subsystem provided the contractor furnished all programming and other software necessary to produce a system functionally equivalent to that specified.

The computer system provides the interface between the control console and displays and the communications system. Figure 7 shows the rack containing the computer, the communication equipment, and the analog chart recorders.

Quality Control. An important feature of the specification written for construction of the control system was the inclusion of a number of requirements to assure the quality of the installation. These requirements were:

1. Prequalification of bidders
2. Inherent availability requirement
3. Acceptance testing
4. Operational availability demonstration

The prequalification procedure was specified to ascertain whether a prospective bidder was technically qualified to manufacture, install, and test the operation of the equipment. The procedure included an inquiry into a prospective bidder's experience, technical personnel, quality control, and plant facilities. This prequalification questionnaire is included in Reference 1.

The inherent availability requirement directed the successful bidder to perform an availability analysis of the system he proposed to provide. The quality of equipment and the amount of redundancy were required to be suitable to provide a 96.5% calculated availability. This requirement appears to have served its purpose by leading to a judicious selection of reliable equipment. At the same time, it was not so stringent as to cause needless expense to the contractor.

The acceptance testing requirements were not unusual. They consisted of the normal checkout of all the components furnished and system operational testing.

The operational availability demonstration requirement, however, was quite different from that usually specified. It was included to provide some measure of

Figure 7. Computer, Communications, and Analog Rack—South Bay Control Center

control over the contractor during construction to ensure that the Department received a reliable system.

The availability demonstration required the Department to use the system during a six-month period after it had been installed and checked. During this period the system had to be operational at least 95% of the time with a MTBF (mean time between failures) of greater than 50 hours. The contractor was to perform the system maintenance, with failures being logged by the Department. When failures were too frequent or existed too long, the contractor had to continue the demonstration for a longer time.

Construction of the South Bay Aqueduct Control System

Work performed under Specification No. 65-33, South Bay Aqueduct Control System, consisted of furnishing and installing a computer-based digital control system on the South Bay Aqueduct. This system enabled the Aqueduct to be monitored and controlled from the South Bay Control Center located at the Delta Operations and Maintenance Center. It also provided for future remote control from a Sacramento control center.

The work included miscellaneous structural and instrumentation revisions and additions required to make the instrumentation and control equipment provided compatible with the existing aqueduct facilities.

The work also included the calibration and testing of all devices furnished and controlled, furnishing of system maintenance manuals, maintenance of the system for two years, and training of department personnel in the operation and maintenance of the system. Table 3 summarizes the contract data.

Sacramento Control Center (Stage 2)

Design of the Sacramento Control Center

An important part of the South Bay Model study was the Sacramento Control Center. This equipment served as a separate remote control center and as the

Table 3. Summary of the South Bay Aqueduct Control System Contract Data

Specification	65-33
Low Bid Amount	$772,460
Final Contract Cost	$1,094,199
Total Cost—Change Orders	$291,411
Starting Date	1/5/66
Completion Date	12/31/68
Prime Contractor	Aetron—Division of Aerojet General Corporation

interface between the South Bay system and the Stage 4 control computer, which was to test real-time computer control.

Design of this facility was begun before the contract for the South Bay Aqueduct control system was awarded and was completed less than a year after construction of the South Bay Aqueduct system had started. During the early design period, a minimum system interdependence was planned and was restricted to the communication line. The only feature of the interface which depended upon a decision by the South Bay Aqueduct system contractor was the selection of a modem (see Chapter V, Section on Standard Communication System). Other features of the interface had been determined previously and were thus included in the design of both facilities.

The Sacramento Control Center consisted of consoles and displays for remote operation of the South Bay Aqueduct facilities. The consoles and displays were located in the Department's Sacramento headquarters building adjacent to the Stage 4 control computer. The Sacramento Control Center was specified to incorporate a computer as a result of AETRON (the low bidder) electing to exercise the computer option of the Stage 1 specification.

The control console had a separate console for each kind of controlled structure; for example, there was a console for pumping plants, another for check structures, and so forth. The console for check structures had all the controls, alarms, and displays necessary for check structures; and windows for display of gate positions with the largest number of gates, upstream and downstream water level, setpoint, and others.

This concept had some serious drawbacks. One was that a console would require provisions for any rare readout or control, even if it were used at only one location. Another was the wide variety of structures which required a large number of consoles and caused operations to be confusing and difficult.

Within the limits of its design, the Sacramento Control Center worked well with the South Bay Aqueduct Control System and enabled the completion of the testing and evaluation for which the Model was developed. Figure 8 shows the Sacramento Control Center consoles and displays.

Construction of the Sacramento Control Center

Work performed under Specification No. 66-26, Sacramento Control Center, consisted of furnishing and installing a computer-based control center com-

Figure 8. Consoles and Displays—Sacramento Control Center

plete with operator console, display panels, cabling, and communication interfacing electronics. This equipment enabled the operator to control the South Bay Aqueduct from Sacramento. The equipment was installed on the 16th and 17th floors of the Resources Building in Sacramento.

Following installation, work included testing to demonstrate operational capabilities, maintenance of the system for one year, system maintenance manuals, and training of department personnel in the maintenance and operation of the system. Table 4 summarizes this contract.

Table 4. Summary of the Sacramento Control Center Contract Data

Specification	66-33
Low Bid Amount	$349,700
Final Contract Cost	$451,277
Total Cost—Change Orders	$83,836
Starting Date	7/11/66
Completion Date	6/18/70
Prime Contractor	Philco-Ford Corporation

Communications Lease (Stage 3)

The communication circuits between the Sacramento Control Center and the South Bay Aqueduct were leased from the Pacific Telephone and Telegraph Company. Details of this lease arrangement are discussed in Chapter VII, Communication Systems.

Computer System (Stage 4)

Computer Hardware Acquisition

As a part of the early design activity, documented in Reference 1, functional requirements were developed for the control computer hardware to be used in the Sacramento Control Center. These requirements were set forth in a request for proposal (RFP) which was released to 24 computer manufacturers and systems firms in September 1965 (Reference 2). In response to this RFP, four proposals were submitted. These proposals were evaluated by both the Department and the consultants for both technical conformation to the RFP and cost. The results of this evaluation indicated a lease contract should be awarded to the UNIVAC Division of Sperry Rand Corporation for a Model 418-II computer system.

Computer System Programming

Since the Control System Model study was a "research and development" type of activity, it was decided that the programming of the control computer should be accomplished "in-house" by a team of engineers and programmers rather than to contract this activity outside the Department. The Department believed it essential to develop this capability within its own staff since this expertise undoubtedly would be necessary for future control system activities. The programming consisted of developing software for both a complete, computer-controlled, automatic operation of the Aqueduct and an operator-guide operation. This programming was accomplished between early 1966 and 1969.

The general-purpose computer software, such as the executive routine, the assembler, and other utility programs, was supplied by UNIVAC. The programs needed to operate the Aqueduct and to interface with the UNIVAC software were written by a departmental team including engineers with civil, electronic, or electrical backgrounds and computer programmers. The programs were written in assembly language.

Programs were written for two modes of computer operation: (1) operator guide; and (2) real-time, on-line, computer control. Both of these modes were tested on the Model to determine their applicability to the main line (California) Aqueduct operation.

The plan for operator guide involved having the computer monitor and analyze different operating situations. The computer received data and status from each of the sites, analyzed this information, and typed suggested advice to the operator. The operator was free to accept, modify, or reject the advice.

On the other hand, the plan for real-time, on-line, computer control provided complete command and control capability from the computer. The computer would perform the same monitoring and analysis functions as in the operator guide but, in addition, automatically form and send the communication messages necessary to control the facilities.

The various programs required for computer control of the Aqueduct were divided into six categories. Specific details on these categories and the associated computer software are beyond the scope of this report. However, a general explanation of some of the programming philosophies follows:

Master Control Program. This program monitored and directed the lower-level application program. It selected the proper program at the proper time, utilizing the real-time clock, and determined the sequence of execution by a priority system.

Water Delivery Schedule Program. From the available water, pumping capacity, and water delivery requests, a schedule was developed of the amount of water to be delivered at each turnout at the designated time.

Because of the small number of water users and the absence of electrical power generation or water availability limitations, the water delivery program for the South Bay Aqueduct was relatively simple.

Information Control Program. This category contained the "bookkeeping" programs. Status of all project facilities and related data were monitored by these programs. Information was kept up to date and available to programs in other categories.

The information storage consisted of a number of sublevel routines which accomplished bookkeeping tasks that were specifically oriented to aqueduct operation. A main function was "data/status storage". When data or status messages were received by the computer, this routine, among other things, checked the message for parity and activated the data/status storage routine. Then the message was repacked into a designated storage area known as the "data/status table". When the new information was stored, its time of reception was also placed in an adjacent storage location thereby maintaining an up-to-date storage of information regarding project data and status.

Daily Operations Program. This category of programs generated a plan for normal operation, giving the day's entire flow requirements for all check structures, pumping plants, and turnouts. If the customer's water delivery requests changed during the day, this program would recompute new flow requirements to meet the change.

The daily operation plan used the water delivery schedule and data/status tables to derive a daily operations plan table. The plan table was a list of all required individual site activities and when they were to be performed in order to satisfy the water delivery schedule. The plan used sophisticated control algorithms in order to minimize any possible hydraulic surges due to a planned flow modification.

System Operations Program. From the daily plan and flow requirements, this program selected the proper check and positioned its gates, selected and controlled the pumping units, and opened or closed the appropriate turnouts. This program performed the operation of actual water delivery to customers.

The programs in this category were designed to route all commands through a jurisdictional control software matrix. If the operational mode was computer control, the command was permitted to leave the computer for the designated site. If the mode was operator guide, the command was typed out to the operator for execution.

Systems Alarm Program. Responses to all abnormal and emergency conditions were responded to by this category of programs. There were two types of alarms involved: (1) those that came from instrumentation and equipment at the sites, and (2) those that were generated within the computer by analysis of the data it received. At the time an analysis was being performed, these programs called on other categories to supply current conditions of project facilities and, if necessary, called upon another section to initiate a command. The alarm condition might also require that the daily operations plans be rerun because the system could not carry out the previously generated operations plan.

Results from the Model Study

Although many problems, both developmental and technical, combined to delay completion of the test and evaluation of the South Bay Model until 1970, many benefits accrued prior to completion to make the program of great benefit to the Department's total control system effort. These benefits were realized concurrently with the planning, design, and construction efforts, and their impact was felt on other control system activities even before the Model was completed.

Experience gained on the Model was invaluable in the design and construction of the remainder of the project control system. Many technical problems which were discovered on the South Bay System were avoided on the main-line control system. Certain organizational changes also were made within the Department relative to the design and construction of aqueduct control systems. These changes enhanced subsequent control system activities.

The feasibility of using computers, both as building blocks in system design and in an automatic control environment, was firmly established.

The consultants' participation was invaluable in assisting the Department in gaining experience during the design and construction of the Model. This, in turn, allowed the Department to proceed with the implementation of the main control system without the use of consulting engineering firms as had been planned for Phases 2 and 3. Consulting assistance was not proposed in Phase 4.

All of the equipment designed and constructed during the Model study is now being utilized. The South Bay Aqueduct system is in continuous use in the operation of the South Bay Aqueduct. The Sacramento Control Center equipment has been relocated and converted to a control simulator for training of hydroelectric plant operators. The UNIVAC computer has been expanded and forms the foundation for the Project Operations Control Center.

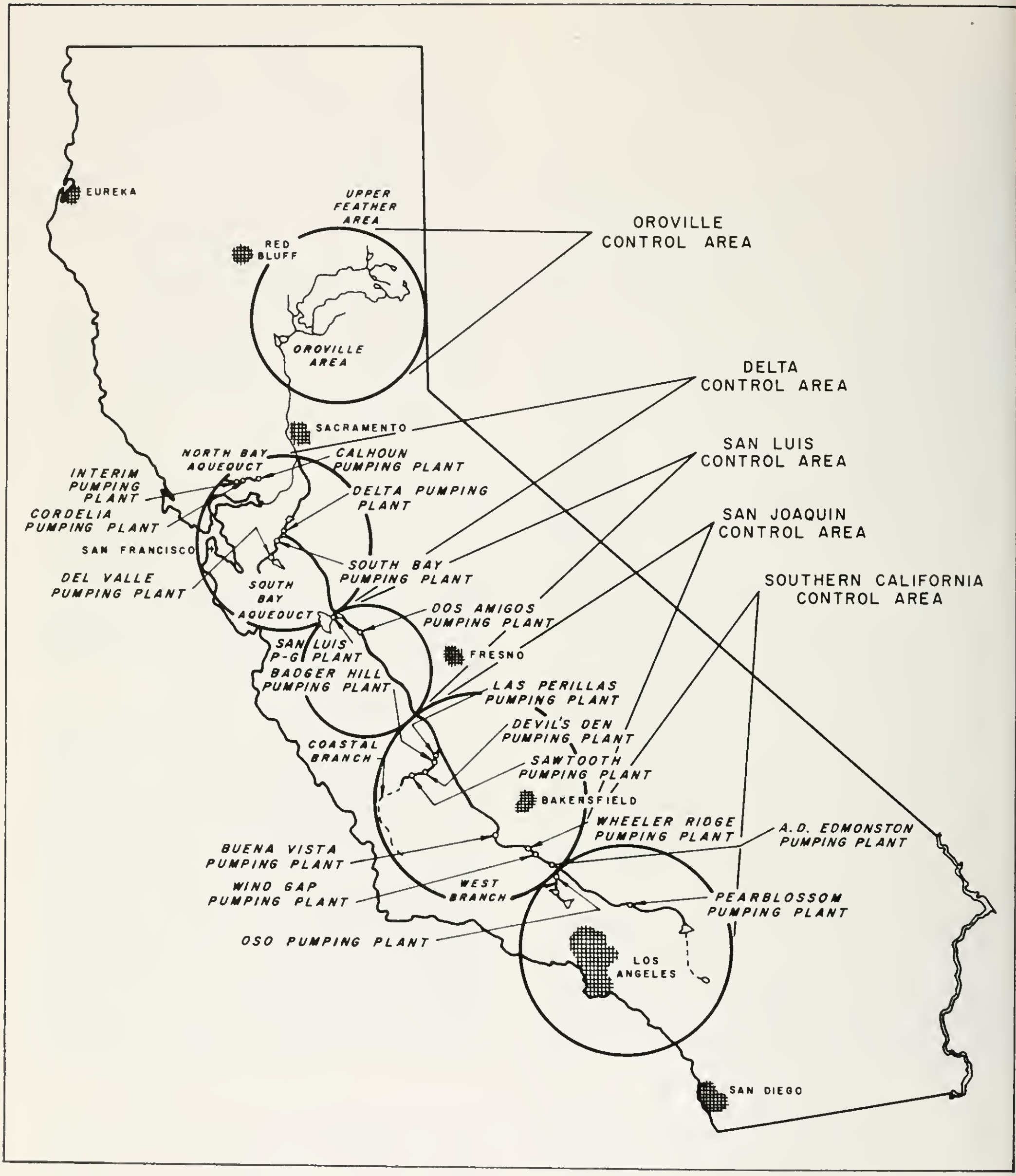


Figure 9. Control Area Boundaries—State Water Project

CHAPTER IV. OPERATIONS CONTROL PLAN

During construction of the South Bay Model, it became evident that the results of the Model were not going to be available until after the time that design of the remainder of the Project's control systems had to be started.

Thus, the Operations Control Plan for the State Water Project was developed to provide the preliminary criteria and guidelines by which the control system would be designed and constructed. This plan (completed in 1965) was jointly developed by members of the design, construction, and operations and maintenance staffs.

The purpose of the Plan was fourfold: (1) reassess the overall guidelines, criteria, and basic control concepts for the project control system as originally conceived and discussed in Chapter II, "Planning Considerations"; (2) furnish information about the control system for use in refinement of operation and maintenance activation work, such as manpower requirements, organization, and operating procedures; (3) provide a definition of the control system for use as needed by all offices in the Department; and (4) provide the control system interrelationship between facilities of all divisions of the Project.

Control System Plan

The Operations Control Plan as developed defined the structure of the control system and the operational relationships between the individual facilities to be controlled. The Plan requires a remote manual control system with expansion capability to a fully automated system.

Control System Structure

The control system structure consists of five control areas which are located geographically to encompass all project facilities. An area control center is located within each of the five control areas and is the normal point of control for all facilities within that area.

A Project Operations Control Center, located in Sacramento, is responsible for coordinated operation and jurisdictional control over the entire State Water Project.

Control Areas

The five control areas of the State Water Project are Oroville, Delta, San Luis, San Joaquin, and Southern California. Figure 9 shows the boundaries of the five control areas.

Oroville. This control area encompasses the entire Oroville-Thermalito complex and the Upper Feather River facilities, with an area control center located at the Oroville Switchyard.

Delta. This control area encompasses the Peripheral Canal, the North Bay and South Bay Aqueducts, and the North San Joaquin Division of the California Aqueduct. Facilities within this area are controlled remotely from the Delta Area Control Center located in the Delta Operations and Maintenance Center.

San Luis. This control area encompasses the San Luis Division of the California Aqueduct and includes San Luis Dam and Reservoir (joint facilities of the Department and the U. S. Bureau of Reclamation). Facilities within this area are controlled remotely from the San Luis Area Control Center located in the San Luis Pumping-Generating Plant building.

San Joaquin. This control area encompasses the South San Joaquin and Tehachapi Divisions of the California Aqueduct from Kettleman City to the Tehachapi Afterbay and includes the Coastal Branch. Facilities within this area are controlled remotely from the San Joaquin Area Control Center located in the San Joaquin Operations and Maintenance Center.

Southern California. This control area encompasses the East Branch Aqueduct from Tehachapi Afterbay through Lake Perris and the West Branch Aqueduct. Facilities within this area are controlled remotely from the Southern California Area Control Center located in the Southern California Operations and Maintenance Center adjacent to Castaic Dam.

Operation, Measurement, Control, and Display Requirements

Project operation requirements were analyzed, and basic measurement, control, and display requirements were established for the area control centers and for aqueduct and plant facilities.

Within each of the control areas of the State Water Project, capability for complete remote manual control is provided from a control console located in each area control center. Capability for control of each individual aqueduct site or plant is provided locally from a site control panel for aqueduct facilities or from a plant control room for pumping and power plants. In addition, at plants, a level of control is provided from the unit control boards. A complete outline of the specific requirements can be found in Reference 3.

A general summary of the capabilities from each level of control follows:

Unit Control Boards—Plants. The unit control board provides for operation of pumping and generating units and all pertinent auxiliary equipment without depending on any control signals from either the plant control room or the area control center. The plant operator is provided with all monitoring capability required to ensure proper performance of the unit. Displays are also provided by indicating meters.

Plant Control Room. The plant control room consolidates the operation of all unit, switchyard, station service, and plant auxiliary functions from a single location within the plant. This control is accomplished without dependence on any signals from the area control center.

The plant control equipment provides complete startup and shutdown sequencing of the units with monitoring and alarming capability. Alarms and events are automatically recorded. Displays consist of indicating displays and selected recording.

Local Check Structure Control. The local check structure control from the control building adjacent to the check structure provides capability to monitor and control all functions at a check structure. Gate positions are controlled and monitored, and water levels are monitored and recorded.

Local, automatic, water-level control capability is required whereby gate positions are automatically controlled to maintain a given water-level setpoint either upstream or downstream of the check structure.

All control is possible without dependence on any signals from the area control center.

Turnout Control. Major turnouts are provided with both monitoring and control capabilities. A major turnout is one with a design capacity greater than 5% of the capacity of the aqueduct reach in which it is located, or 200 cubic feet per second,whichever is less. Minor turnouts require monitoring capability only.

Other Site Control. Other facilities, including dams, reservoirs, flow measuring stations, and water quality monitors, may require monitoring and/or control capability locally and, in some cases, from the area control center. As the need arises, such capability will be incorporated.

Area Control Center. The area control center consolidates operation of all remotely controlled sites within the area. It is not provided with capability to monitor or control facilities of another area.

The area control center communicates through local plant control systems or other aqueduct local systems to provide control capability. Data monitoring is provided to the level necessary to ensure proper operation and surveillance of all facilities.

Project Operations Control Center

The Project Operations Control Center (POCC), located in the Resources Building in Sacramento, is provided with capability for complete monitoring and dispatching of project operation, complete jurisdictional control, expansion capability to full real-time computer control, and back-up control for any aqueduct area control center.

This control center monitors area operations, records water and power data, develops overall system water and power schedules, optimizes water and power allocations for the Project, and coordinates interarea functions.

To accomplish dispatching and coordinated operation, the POCC is provided with the capability to monitor and display the same functions as the area control centers. Operation of the POCC is not dependent on operation of any area control center equipment. Information concerning actual project conditions is transmitted directly from each remote site, thus bypassing the area control center.

Control and display capabilities necessary to assume control of any one of the aqueduct area control centers are provided. Direct control capability of all area facilities can be accomplished without going through, or depending upon, any equipment in the area control centers.

Preparation of water and power schedules is done by an on-line computer located in the POCC. This computer will automatically compute all schedules and transmit these schedules to the area control centers through remote input-output devices. This computer system acts as the control point from which emergency operation of the Project will be conducted.

Communications System

Communications are required to tie the remote aqueduct sites to their area control centers and the area control centers to the POCC. Two types of communications are required, data and voice.

Data Communications. Data communications are required to provide information exchange between remote aqueduct sites and area control centers. Also included are data communication requirements from the area control centers to the POCC for both data and the computer's remote output devices.

Speed requirements for data communications are dictated by the need to control the facilities to their required precisions and permit complete updating of all information from an area within a two-minute period.

Extra capacity is provided in the initial primary communications along the Aqueduct to allow for future expansion of the system.

Voice and Teletype Communications. In addition to data communications, certain voice and teletype communications are required for information exchange between various points within the Project. These communications are carried out between each remote site and the area control centers, between the area control centers and the POCC, and between the POCC and other operating agencies.

CHAPTER V. CONTROL SYSTEM DESIGN

Following completion of the design of the South Bay Aqueduct Control System Model facilities in 1966, the plan and schedule were reviewed for design and construction of the California Aqueduct Control System and the control systems for the Project's plants and the Oroville-Thermalito complex.

It became apparent that if control systems for the Aqueduct and plants were to be in operation near the time the facilities themselves were to be placed in operation, the Department could not wait for the entire test and evaluation period for the South Bay Model to be completed. It was deemed essential that control of facilities be implemented as near as possible to the time they were placed in operation in order to minimize operational costs and operational errors.

Thus, the Department embarked on the design of a remote manual control system which would have the capability for expansion to a fully automated system in conformance with the operations control plan.

To ensure compatibility between the various designs, certain criteria and mandatory specification requirements were developed prior to the start of the major design activities.

Control Systems Consulting Board

As discussed in Chapter II, as of 1962 Phases 2 and 3 contemplated the use of consulting engineering firms to assist the Department in preliminary systems design, final design, and development of contract specifications. By 1966, however, the Department had developed the necessary expertise to design, construct, and place in operation the various control systems. Nevertheless, it was deemed desirable to provide additional expertise to review the staff's work to ensure that the full spectrum of technological information was available for the system designs.

Accordingly, in September 1966, the Department retained a board of consulting engineers to provide overall guidance during the implementation of the project control system.

Three consultants with experience in the fields of communications, computers, and control systems were retained as the Control Systems Consulting Board. Mr. Russell G. Hornberger, (deceased) Chairman of the Board, had long experience in the design, construction, and operation of large-scale plant and aqueduct facilities. Mr. John T. Clabby (deceased) was a recognized expert in the field of computers and control systems. Mr. Edward W. Messinger, Jr. is a recognized expert in the field of communications engineering. Upon the death of Mr. Clabby, Mr. Theodor H. Braun was retained as a member of the Board. Mr. Braun is an expert in the field of computers and software development.

The Control Systems Consulting Board continued its role of providing general technical guidance to the Department until major system design had been completed. The Board was dissolved in June 1973, after having served for nearly seven years.

System Implementation Plan

Since the decision had been made to have the various control systems made operational as near as possible to the time the associated project facilities became operational, it became necessary to define the method by which all systems would be implemented. A single contract in 1966–67 would have represented a capital investment of from 20 to 30 million dollars, with a construction period stretching over as much as 10 years. A single contract of this magnitude over such a long period of time would have presented design and contract administration difficulties and would have precluded state-of-the-art advances in control system equipment from being utilized in the Project's control systems as they became operational.

Multiple contracts, on the other hand, presented other difficulties. Since all the various systems ultimately would have to be integrated into a single projectwide system, they all had to be compatible in certain areas of system design in addition to being functionally similar. Multiple contracts also had a long-term operation and maintenace disadvantage in that there could be no assurance of like equipment between the various contracts.

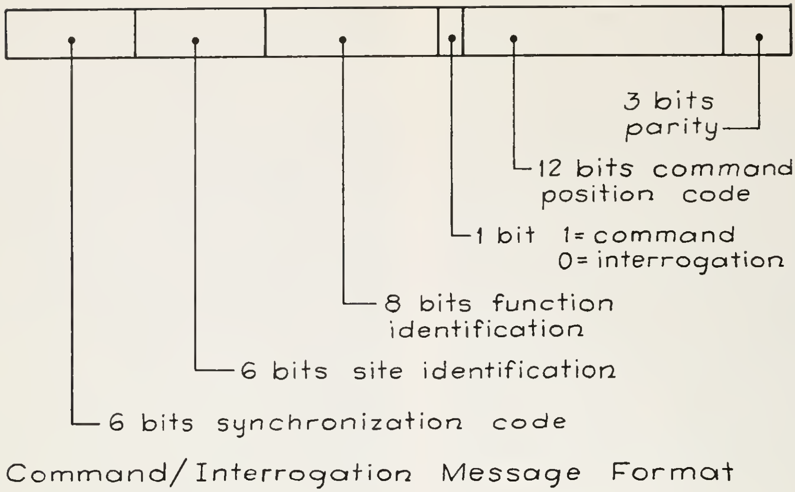
All factors considered, the decision was made to implement the control systems with a series of contracts, with the Department assuming responsibility for compatibility between the various systems. This decision dictated the requirement for certain uniformity between the various contracts.

Design Requirements

Design Criteria

Detailed criteria for the design of the control systems were developed as a joint effort of the operations and design staffs of the Department. The requirements of the systems, including the structure and the functions to be monitored and controlled at the various facilities (aqueducts, plants, area control centers, and the Project Operations Control Center), were contained in the "Operations Control Plan" (Reference 3). These requirements were jointly reviewed by operations and design personnel as to their effect on the designer's operational concepts and as to the availability, feasibility, and economics of equipment to satisfy the requirements.

Final design criteria consisted of the control functions, alarms, data, and status which were to be included at each structure and control center. Where appropriate, characteristics, such as range, accuracy, precision, timing, and other details, were included. These criteria were organized to specify the monitor



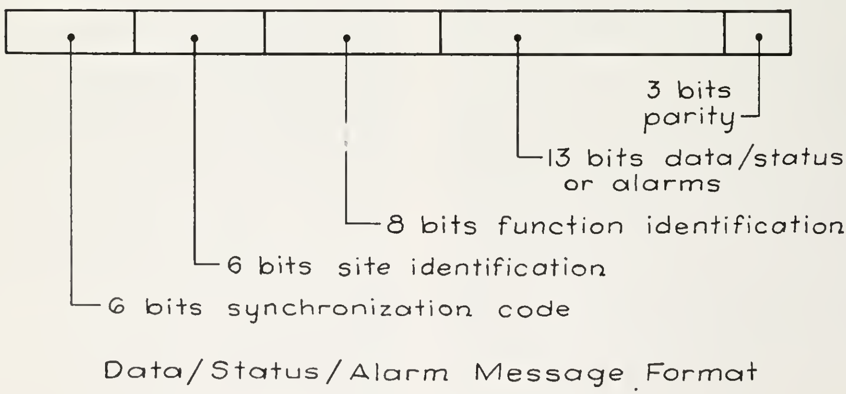


Figure 10. Communication Message Formats

and control requirements locally (at the structure or device controlled), at the local control station (e.g., inside the control building at a check structure), and at the control centers.

Although there have been additions to the control requirements, the original criteria are still the bulk of those actually being used in the control system.

The design criteria also dictated much of the control system design by generating such requirements as speed of control, frequency of monitoring, number of points to be controlled, and degree of accuracy and precision required for measured variables.

Communication Philosophy

A mandatory design requirement for all systems was the method of communication to be utilized between the remote sites and the control centers. This communication was selected to be serial digital in format to meet the high degree of accuracy sought, the large number of points to be monitored, and the problems created by the large distances involved.

Digital data handling has some disadvantages when compared to analog data. During the design period in 1966–67, digital data handling was an intrinsically more expensive approach, particularly where the number of data points at one location was small. It also generally required higher transmission speeds for a given data updating rate because all data had to be time shared on a communication line.

Digital data handling has two major advantages, however. It permits a greater number of significant digits in a measurement, and it does not lose accuracy with transmission to distant points. These two advantages proved decisive in view of the design criteria supplied.

Serial digital communications made it possible to serve all sites and all data points within a control area on no more than two sets of communication lines. This was based upon being able to monitor 1,000 data points within a two-minute period on a single set of lines.

Communication Message Format. All communications between facilities are accomplished by exchange of commands; interrogations; and data, status, and alarm messages.

A command is a message sent from a control center to a remote site and contains control information, either in the form of a setpoint (gate position, water level, and so forth) or a command action like start pump.

An interrogation is a message sent from a control center to a remote site as a request for the site to respond with a data, status, or alarm message.

Data, status, and alarm messages are sent from a remote site to the control center and contain quantitative measurements of parameters (data), conditions such as units in service, switchyard breakers closed (status), and alarm conditions.

The method and arrangement of the various bits (binary digits) within the coded message allow information to be transferred and be intelligible after the transfer has been completed. Prior to design of the message format, it was necessary to determine the extent of future project requirements to ensure that the system would be capable of handling any possible future expansion. The message format which evolved after considerable study was a 36-bit digital "word".

The message format was designed with sufficient bits to identify all the sites which could be connected to a communication line, all the information points which could occur at one site, and also to provide an information portion of 13 bits for quantitative data pertinent to each point. For status and alarm messages, the information portion can carry 13 alarm conditions or 13 status points per message. For data messages, the information portion can contain an unscaled decimal value of 4,095 plus sign, or an unscaled decimal value of 8,191 without sign. Three additional bits are reserved for message security, which protect against communication line noise.

The other essential part of the communication message is a 6-bit, beginning-of-message (sync) code. This part has a fixed format so that it is always recognized as the beginning of a possible message. Figure 10 shows the format of the various types of communication messages.

Communication Transmission Rate. All communication messages are transmitted at a rate of 1,200 bits per second. This rate was chosen to provide a 1,000 point per communication line, two-minute, data update rate. Approximately 120 milliseconds are required for each message exchange to be completed; a total of 60 milliseconds to clock the message in and out of the remote site, 12 milliseconds site response time, and an average of 48 milliseconds for a two-way communication line propagation delay.

Standard "data-sets" or "modems" were also available at this speed. Leased telephone lines capable of operating at this speed with acceptable error rates were readily available and of proven reliability. Studies showed that bit rates faster than 1,200 would reduce reliability and increase costs without a commensurate increase in the capacity of a line.

Communication Protocol. The communications system is operated in a "polled" environment. In this environment, each data, status, or alarm message is interrogated from the control center and the answer received before the control center issues the next interrogation. If, for some reason, the interrogation is not answered, the next interrogation will be sent after a suitable delay period (usually about 100–200 milliseconds).

A polling technique was chosen to allow flexibility to alter the interrogation scan sequence or to interrogate selected points more frequently than once every two minutes.

Redundancy of Communications. Another design feature was the provision for back-up communications to each major site from the control center. This is accomplished by approaching each site with communication lines from two geographically separate routes. A primary or "A" line is routed to each site in turn from the control center by the most direct route, usually along the Aqueduct. A back-up or "B" line is routed to the end of the aqueduct section and, starting with the last site, comes into each site in reverse order and from the opposite direction.

A more detailed description of the actual communication line routing is contained in Chapter VII, "Communication Systems".

Security of Communication Transmissions. Although the communication lines leased from telephone companies are reliable and a high degree of availability has been achieved, they are still subject to certain error-producing phenomenon and catastrophic failure. The most prevalent communications problem is that of impulse noise.

The aqueduct cable, which forms the entirety of the "A" route from an area control center (ACC) and a substantial portion of the "B" route, is almost immune from random impulse noise because it does not pass in proximity to other communications, does not go through telephone exchanges, and is shorter. The "B" route suffers from random impulse noise, which causes some message failures due to the higher "error rate". This effect is shown by more frequent single-message failures due to bits in the message being changed by impulse noise. Messages lost in this manner are usually recovered on the next interrogation scan so that the effect of impulse noise on the control system's effectiveness is minimal. Messages altered by impulse noise are detected by a parity checking scheme contained in the message format.

Three bits of parity are used in the security scheme. The (P_1) parity bit is odd parity on bit numbers ($3N+1$), P_2 is odd parity on bit numbers ($3N+2$), and P_3 is odd parity on bit numbers ($3N+3$), where N is an integer from 1 to 9 (Figure 11). Parity computation is not required on the 6 bits in the sync code. This cyclic parity scheme protects 100% against undetected message errors resulting from 3 adjacent bits or less of the message being in error. Using a communication line error rate of 1 in 10^5 bits, this parity scheme will detect message errors so that only 135 out of 10^{10} messages sent will contain an undetected error.

Additional security techniques have been applied to command messages to guard against the possibility of invalid commands causing false operations.

Two types of catastrophic failures which are most likely to occur on the communication lines are line breaks and induced, high-amplitude, white noise (noise which contains equal distribution of frequencies over the entire band width of the communication channel).

With dual-routed facilities, the effect of a single line break is minimal if both routes are in continual use (the alternate route is an active system). The Project's data communications operate in an active mode. Interrogation scans from the ACC or POCC are alternated for each cycle between the "A" and "B" routes. Data responses from the sites are sent back to the ACC and POCC simultaneously over both routes. This method takes advantage of the diversity of routes while facilitating detection of failed communications. When a failure of one interrogation line does occur, it does not make the system inoperable but merely extends the updating time for data to four minutes instead of two. Commands are always sent out sequentially over both lines.

The length of time required for an interrogation and its response is a known value and varies with the distance from the control center to the site being interrogated. This time averages about 120 milliseconds. If the site does not respond, as may happen if the communication lines are not functioning properly or the site itself is inoperative, the control center waits the

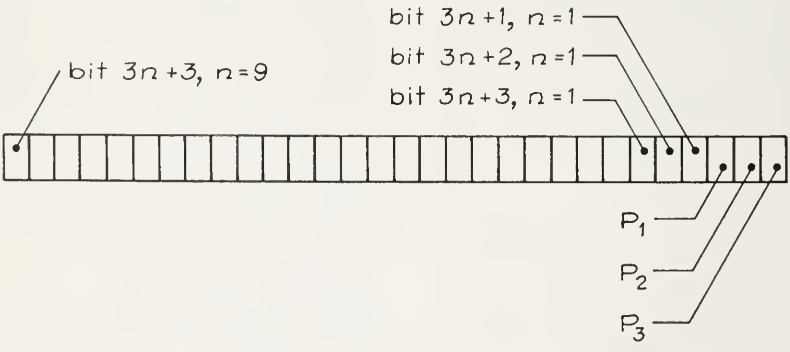


Figure 11. Message Security Scheme

longest expected time (about 200 milliseconds) and then proceeds with the next interrogation. Failures of this kind are compiled and analyzed by the control center computer to determine the probable cause and inform the operator of this determination. Thus, failures can be immediately detected and repair work can begin even though valid data are continually being received.

The second type of catastrophic failure (induced, high-amplitude, white noise) may obliterate some or all actual messages or may simulate a message where one does not exist.

Obliteration of a small fraction of messages is not a serious problem since it does not result in erroneous data but only a delay in information updating. The problem is more serious when the number of messages obliterated is large or includes all the data to or from one of the sites. Simultaneous noise of this magnitude on both "A" and "B" routes is extremely rare.

A more dangerous and less anticipated problem is the synthesis of messages from white noise. This will occur under rather special conditions where (1) there is no signal on the line, (2) the noise is unusually high in amplitude, and (3) the modem receivers are adjusted to be very sensitive. Under these conditions, random messages will be clocked into the system at a rate of 1,200 per second. Since this possibility has the greatest potential for damage when the simulated message is a command, the preventive measures taken apply to commands.

One technique is a reduction in the sensitivity of the receivers and squelching of site receiver during periods of no signal. The other technique to counter the synthesizing of commands is to require double transmission of commands to a site within a specified period of time before the commanded function will be performed. This measure is effective because the probability of synthesizing two identical messages within a short period of time is extremely low.

Standard Communications System. Each remote site and control center is provided with a standard communications system containing modems and special communications terminal equipment. These communication systems are of uniform functional design throughout the entire Project.

Modems are devices which convert direct-current (DC) electrical pulses into appropriate audio frequencies (**modulation**) for transmission on a voice-grade communication line and convert received audio frequencies into direct-current pulses (**demodulation**). They are necessary because high-speed DC pulses cannot be transmitted farther than a few hundred feet over a pair of wires without becoming unintelligible. The modems specified for the control system are compatible with Western Electric Company, Model 202D.

The communications terminal equipment (CTE) is a system of special solid-state, electronic, logic elements which interface the modems to the remainder of the equipment at the site or control center. For incoming messages, the CTE converts the serial data stream coming from the modem into a parallel form suitable for the computer input. It also checks for the presence of the sync code at the beginning of a message. The CTE contains a receive clock which is synchronized by the sync code bits. This clock controls the sampling of the incoming data. Outgoing messages are serialized by the CTE and clocked into the modem. The CTE also exchanges numerous timing and control signals, both with the computer and the modems, to maintain synchronization, to isolate the messages from pulses which could be mistaken for bits, and to place the bits in their proper position within the message.

The actual interface between the CTE and modems was specified to be in conformance with EIA-RS-232B (Reference 4). The interface between the CTE and the computer was left to the discretion of the system contractor.

Equipment and System Reliability

Of primary concern was the order of reliability that could be economically achieved and how it could be accomplished. It was realized that as equipment reliability was increased from that which had been utilized for many years in the water utility industry to that which was being developed currently as part of the space age, the cost of the system would increase commensurately. Another concern was that developments in this type of equipment were being made almost daily and, since control system construction would span many years, design had to be progressive and farsighted to provide for the unavoidable obsolescense which would take place during the design and construction period.

The plan which was utilized consisted of specifying state-of-the-art materials, imposition of quality control requirements, system availability analysis, system testing, system availability demonstration, and contractor prequalification.

State-of-the-Art Materials. Where practical, all components were specified to incorporate semiconductor circuitry throughout, all diodes and transistors were to be of the silicon type, and all electronic equipment was to incorporate integrated circuits.

All equipment and material to be used were to have been in current manufacture at the time of the bid opening. In addition, suppliers of equipment were to have been actively engaged in the manufacture of similar equipment for at least three years prior to the time of the bid opening.

Quality Control Requirements. All contractors were required to obtain department approval on all proposed equipment and adhere to a quality control procedure. This procedure provided for the prevention and ready detection of discrepancies and for timely and positive corrective action. All phases of the contractor's work, whether performed within the contractor's facilities or at other sources, had to be controlled at all points necessary to ensure conformance with contractual requirements. The quality control procedure covered control of purchases, source inspection, in-manufacture inspection, test and checkout, and final inspections.

System Availability Analysis. Within 90 days after receipt of the notice to begin work, the contractor was required to submit an inherent availability analysis of the system he proposed to provide, using the following availability prediction procedure.

$$A_i = \frac{(MTBF)_i}{(MTBF)_i + (MTR)_i} \times 100$$

where A_i = Inherent System Availability (percent)
$(MTBF)_i$ = Predicted Mean Time Between System Failures (arithmetic mean)
$(MTR)_i$ = Predicted Mean Time to Repair a System Failure (arithmetic mean)

Continuation of the contract was contingent upon the contractor successfully meeting a minimum specified availability level. All equipment which the contractor planned to utilize as part of his installation was monitored prior to purchase to ascertain that the quality was commensurate with that on which the above calculation was based. Materiel was rejected or accepted on that basis. The equipment assembly at the contractor's plant was closely monitored to ensure that the most modern and effective procedures were employed and that the assembly was in conformance with availability calculations.

System Testing. Extensive testing was specified at both component and system levels. Each component of each subsystem required testing by the contractor. Where duplication of components occurred, a random sampling technique was used on which complete tests of no less than 10% of the total number of components installed could be employed. The Department reserved the right for 100% testing where required. Additional testing was required where failures occurred in the random sampling.

Following manufacture, the system was required to be assembled at the contractor's facility for a final factory acceptance test. This test included complete operation of all components as a system with simulated inputs and outputs. Upon acceptance, the system was disassembled and shipped to the site for installation.

After the installation work was completed, the contractor was required to conduct operational completion tests to demonstrate compliance with the operational requirements of the specifications.

System Availability Demonstration. Upon completion of all installation and testing, the Department took possession of the systems for use during an operational availability demonstration. During this period of time, which could vary from six months to one year, the Department used the systems and the contractor maintained all the equipment. During a continuous six-month period, the contractor was required to demonstrate that the system met certain minimum availability levels. Failure records were kept and analyzed by the Department, and the availability was calculated using actual MTBF and MTR figures rather than predicted values. If the required level of availability was not achieved within a period of one year after being placed in operation, the contractor would be assessed liquidated damages, which provided funds for necessary modifications to the system.

Naturally, the larger the system, the smaller the required availability level would be, due to the greater number of components where failures could occur. Thus, for each contract, a minimum availability level was assigned on the basis of the total number of components being supplied and installed in that contract. These minimum levels were in the range of 95% for the aqueduct systems and in the range of 99% for the plants.

The specifications limited the total number of failures which would be allowed during the availability demonstration. It was anticipated that a contractor might overcome the quality requirement implied by a high availability requirement by the process of rapid repair of failed equipment (short MTR). To prevent this expedient, a minimum mean-time-between-failures of 50 hours was specified.

To ensure that the failure characteristics developed during the availability demonstration were sufficient on which to base system acceptance, the availability calculation and MTBF rate had to have a confidence limit of at least 95% using the chi-square distribution with the following equation.

$$C_L = \frac{2r}{\chi^2 a{:}2r} (MTBF)$$

Where C_L = One sided lower confidence limit
r = Number of failures
$\chi^2 a{:}2r$ = Chi-squared distribution value for the percentage point corresponding to the specific confidence level and degrees of freedom
$100(1-a)$ = Confidence level (percent)
$2r$ = Degrees of freedom
a = Probability that chi-squared value will be exceeded

Contractor Prequalification. The success of the procedures and techniques developed to ensure system reliability were dependent on the contractors who were required to adhere to them. Consequently, contractor and subcontractor prequalification was required to limit contract awards only to those experienced in this kind of control system implementation.

These prequalification procedures are discussed in Chapter VI, "Control System Construction."

Operation and Maintenance Documentation

A key requirement for all system specifications was adequate documentation of the contractor's hardware and software.

Hardware. Contractors were required to provide the Department with complete instruction manuals for maintenance of the equipment. This requirement included both a system instruction manual as well as various equipment manuals.

The system instruction manual was specified to be a specially written document to convey an understanding of how the system operates and to provide sufficient procedures for operation and maintenance. This manual provides instructions for operation and maintenance of the complete system as opposed to operation and maintenance of individual equipment of which the system is comprised.

The system instruction manual is organized along the following lines:

1. **Introduction**—Contains a detailed description of equipment. The primary purpose of the introduction is to provide a ready orientation to the use and purpose of the manual and its relationship to the equipment manuals.

The extent, content, and limitations of maintenance covered by the manual are explained in this section. The section also includes special circumstances and environmental considerations, if applicable.

2. **Safety Precautions**—Describes all major hazards to personnel and equipment and safety considerations that are peculiar to the equipment or jobs covered in the manual. The information is in tabular form wherever practical.

3. **Description of System**—Provides a physical and functional description of the system in its operating environment but does not describe in detail the individual equipment in the system.

4. **Physical Description**—Describes the physical features of the system and their general arrangement. It also provides a brief description of the major components of the system, their location, and relationship to the complete system.

5. **Functional Description**—Explains how the system functions as an integral unit.

6. **System Operating Instructions**—Contains the necessary information required by maintenance personnel for operation of the equipment and includes such instructions as necessary for setting up or preparing the equipment for use, warm-up procedures (if applicable), starting the system, verifying normal operation, shutdown, postshutdown, and emergency procedures.

Emergency procedures consist of actions to be taken by an operator or maintenance technician in the event of malfunction.

Detailed step-by-step procedures, or specific sequence of accomplishment, if required, are presented in tabular or checklist form to the maximum extent feasible.

7. **System Maintenance Instructions**—Contains the applicable checkout, trouble shooting, servicing, remove and replace, and inplace-repair procedures which are performed on a system basis.

8. **Checkout Procedures**—Provides checkout procedures required to verify the satisfactory operation of the system or major subsystem as applicable.

9. **Trouble Shooting Procedures**—Serves as a guide in isolating faulty equipment. Also indicates, but does not describe in detail, the corrective action required.

10. **Servicing**—Includes cleaning, lubrication, replenishment of fuel, and other preventive maintenance procedures that apply to the particular equipment.

11. **Remove and Replace Procedures**—Included only when they are not provided in the applicable equipment manuals. The procedures provide step-by-step instructions for removal and replacement of items which are subject to frequent replacement.

12. **Repair Procedures**—Provided only in those instances where the work can be performed in place or on a system basis, or a combination of these. The procedures provide the necessary information to bring the equipment up to the required serviceable standard. If checkout is required to verify satisfactory operation of the equipment, applicable reference is made to the appropriate section of the manual. Reference to the equipment manuals is used wherever possible.

13. **Wiring Diagrams**—Includes power distribution and control wiring diagrams with associated data required to understand the structure, arrangement, and function of the system (simplified functional or logic-type diagrams are sometimes used); trace circuits; procedures to make continuity checks; and general and specific trouble shooting techniques for inoperative or malfunctioning circuits.

Equipment manuals, on the other hand, consist of an organized assembly of maintenance and operating manuals, bulletins, brochures, and other data normally furnished by the manufacturer with his equipment. Supplemental data are included to augment that normally provided by the manufacturer.

These equipment maintenance manuals include information and data in sufficient detail to permit a trained technician to troubleshoot, diagnose, and repair the control equipment and peripherals including the power supply and the CTE equipment. The following specific subjects are covered in detail:

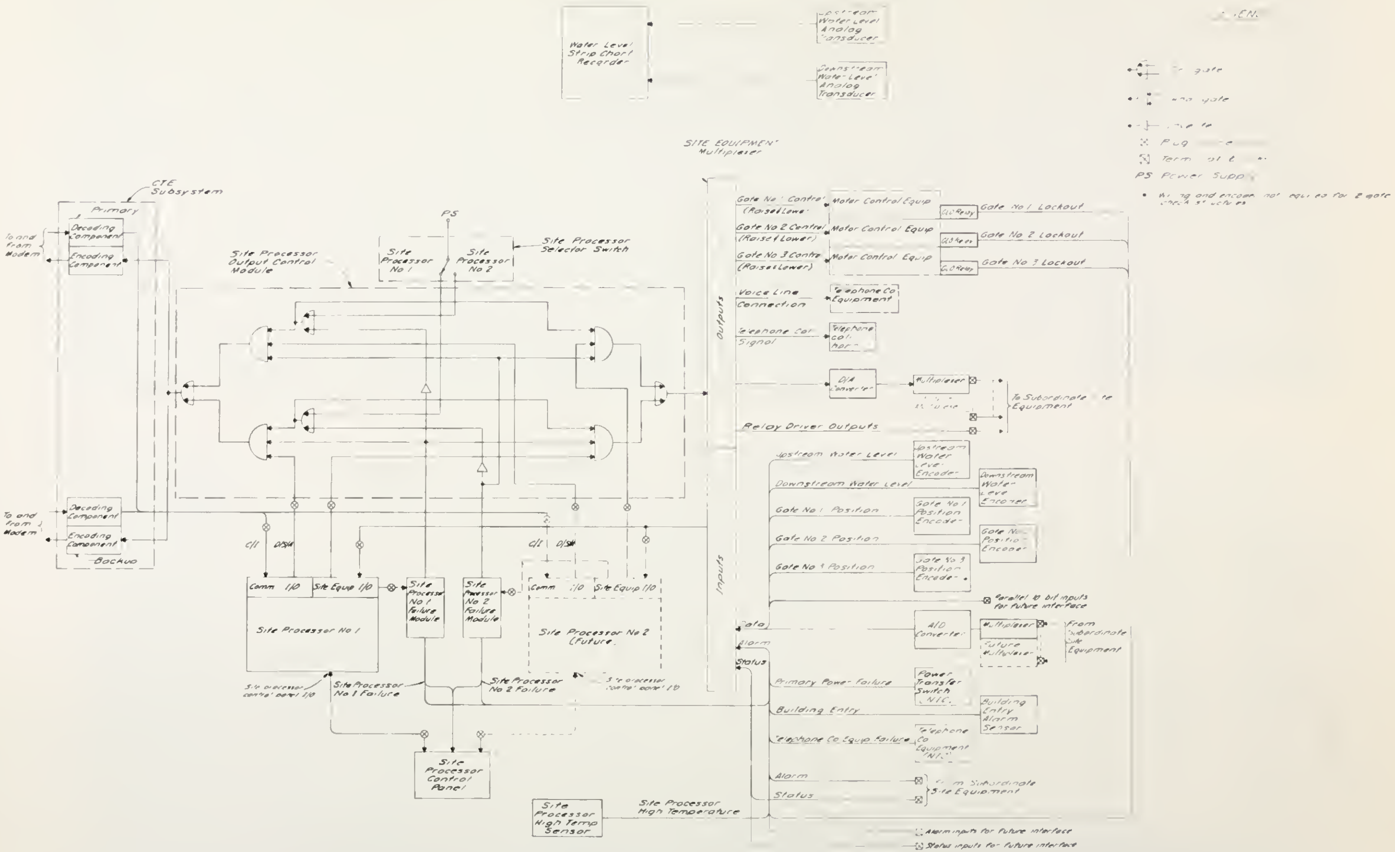


Figure 12. Functionol Block Diagrom—Check Structure Control System

1. Description of equipment
2. Normal operating procedures
3. Emergency operating procedures
4. Preventive maintenance
5. Calibration
6. Repair and replace instructions
7. Complete schematic diagrams
8. Complete wiring diagrams
9. Parts list for each component or device, manufacturer's stock or catalog number, quantities used, descriptions, and illustrations.
10. Component value and rating designations for all components, devices, and equipment regardless of whether or not the manufacturer's stock number is furnished.
11. Recommended spare parts list
12. Voltage and current or similar test point data
13. Trouble-shooting procedures for central processor units and other equipment.
14. Timing diagrams relating to control and monitoring under program control.

Software. The contractors also were required to document all of the software they developed for the various systems. This documentation includes:

1. **General Description**—Presents the overall purpose of the computer program. All assumptions by the contractors are stated along with their logic. Formats for the input and output messages also are described.
2. **Abstracts**—Describe the operational objectives for each major section of the program logic and includes the relationships to other major sections.
3. **Nondependent Flow Chart**—Each major section of the programming logic is presented in greater detail than for minor sections. This detail is developed into a format of flow charts using statement and decision blocks with lines connecting these blocks to show the flow of information. Within each statement and decision block, sufficient information is presented to describe what is being accomplished.
4. **Dependent Flow Charts**—Describe the nondependent flow charts in such detail that a real-time programmer can directly accomplish the required coding. They are developed in a flow-chart format using statement and decision blocks with lines connecting the blocks to show the flow of information. These flow charts incorporate the capabilities of the specific processor and programming language being employed.
5. **Assembled Listing**—A complete and fully debugged assembled listing is furnished of all coding required for successful execution of supplied software programs.

The listing includes location counter values (P-register values), machine language operation codes, machine language operands, coding labels, mnemonic operation codes, mnemonic operands, and comments.

6. **Memory Map**—A map is provided of the internal storage of the central processor unit. This map shows the numbered locations of the core memory and the information stored in each location.

If a drum or disk-type storage device is used, a map of the device is supplied. The map shows the memory location and the information stored in these locations.

7. **Glossary of Variables**—A glossary listing is included for every variable used in the coding with a label and description for each variable.

Operation and Maintenance Training

The contractors were required to develop and conduct special training courses for the Department's operation and maintenance personnel. These courses, averaging from one to two months in length, covered detailed instructions on the operation, maintenance, adjustment, calibration, and troubleshooting of the hardware components.

Software training also was required, including overviews and details of the software design. This training averaged from two to four weeks in duration.

Design of Check Structure Control Systems

There are 64 check structures along the California Aqueduct of the State Water Project. Their purpose is to control the rate of flow in the Aqueduct by movement of the radial gates to vary the cross-sectional area of flow through the check structure to achieve a balance between flow rate and upstream and downstream water level.

These check structures are spaced from 5 to 10 miles apart along the Aqueduct, depending in part on the design capacity of the reach in which they are located. Each check structure has two, three, or four radial gates, depending on its location in the system.

The gates are positioned by an electrically driven hoist mechanism which is cable-connected to the gate itself. The hoisting mechanism is controlled on-site from either a local control switch adjacent to the hoist on the deck of the check structure or from a motor control center located within the control building associated with each check structure. Water levels and gate positions also can be read locally by means of staff gauges.

The equipment added for control consists of a computer system; an operator's control panel; communications equipment; devices for transducing operating parameters; local, automatic, water-level control equipment; and subordinate site and interface equipment. Figure 12 is a block diagram of a typical check structure control system.

Computer System

The basic element of the control system at the check structures is a small, general-purpose, digital computer system. This computer interfaces with the communication terminal equipment, the local operator's control panel, the various measuring and control devices, and the subordinate site equipment.

Several factors pointed to the possibility that a small, general-purpose, digital computer (the type now referred to as a "mini-computer") might be economically justified for use at check structure sites. These factors were: (1) the high accuracies required, such as 1 part in 300 for gate position and 1 part in

1,000 for water level; (2) the need to encode or decode all communication setpoints and transmission measurements into a binary digital code; (3) the need for dynamic comparisons and control actions, such as actual gate position with gate position setpoints; (4) the need for computational capability; and (5) the convenience of using check structures as gathering points for data and control for turnouts and other subordinate sites.

Studies were made to determine the relative economy and reliability of systems using logic circuits specifically designed for the functions to be performed versus using a general-purpose mini-computer. The studies did not provide an unequivocal answer to these questions but did indicate that a mini-computer was economically competitive at the prices then current and was equal in reliability.

There were other features of the mini-computer which shifted the balance toward its use. When a computer is used for control, changes and additions can be conveniently made to the computer software without putting the controlled equipment out of service or purchasing additional equipment. Computer changes and additions can be made "off line" and loaded into the site computer after the program has been completed and tested. When a computer is used, the required hardware is simpler and more readily available "off the shelf", resulting in easier maintenance and replacement. Proper documentation of program changes is also easier to ensure than is documentation of hardware modifications.

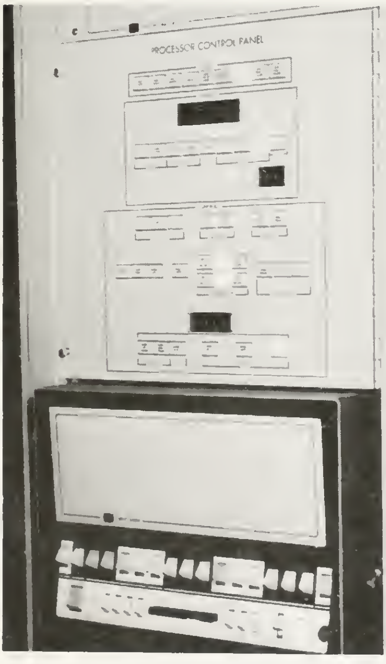


Figure 13. Operator's Control Panel—Check Structure Control System

As a result of these studies, design of the check structure controls incorporated the use of a general-purpose digital computer. At most check structures, this computer is a 4K core memory computer. The computers used at the check structures in the Delta, San Luis, and San Joaquin control areas are Hewlett Packard Model 2114. Those used in the Southern California control area are Honeywell Model 316.

Operator's Control Panel

Each check structure is provided with local operator control capability through the operator's control panel. This panel is the operator interface to the computer for the purpose of monitoring and controlling the various parameters and devices at the structure.

The panel consists of a series of switches, pushbuttons, and digital readouts with which the operator communicates with the system. Figure 13 shows the layout of a typical operator's control panel.

Communications Equipment

The communications equipment consists of the standard communications system installed at all facilities.

Measurement of Operating Parameters

There are two basic parameters to be monitored at the check sites. These parameters are water levels, both upstream and downstream from the check structure, and the position of each gate at the check.

Water-Level Measurement. Water-level measurement is made at float wells located approximately 150 feet upstream and downstream from the check structure. These float wells have been located to allow water-level measurements to be made at points where they are not substantially influenced by water surface fluctuations.

To convert the water level in the float wells to a quantity usable by the control system, a perforated, stainless-steel tape with a counterweighted float is used to drive a sprocketed pulley. A 10-bit, digital encoder is attached to the pulley shaft to provide a gray-code output of the water level. Using this method, water level is measured to an accuracy of plus-or-minus 0.01 foot over a range of 10 feet. This range exceeds the operating water-level fluctuations in the Aqueduct.

Gate-Position Measurement. The height of the bottom of each gate above the sill (the gate position) is a measurement which, in combination with water levels, is used in the calculation to determine flow through the structure. To achieve the necessary precision and accuracy of flow measurement, it is necessary to measure the gate position to a precison of 0.1 foot. Since many of these gates are 30 feet high, this was a significant problem to be solved.

The gates are moved by a motor-driven cable hoist, and it appeared possible to measure the gate position by attaching a digital encoder to measure the angular position of the cable sheave. This method proved impractical because the differential stretch of the cable between raising and lowering is several times greater than the tolerable error. Consideration was given to driving a digital encoder with a toothed pinion riding a rack-mounted chain on the upstream face of the gate, but it was feared that accumulation of debris in the rack would render this method unreliable.

The method finally devised uses a pantograph to transfer gate angular motion to an instrument shaft which drives a digital encoder. The pantograph, shown in Figure 14 designated as a "four-bar linkage", has one member (the gate arm link) rigidly attached to the radial beam of the gate. The angular position of the gate arm link is reflected accurately in the angular position of another member (the instrument shaft link), which is connected to the check structure. The instrument shaft, driven by this link, is coupled to an encoder shaft. Internal gearing in the encoder converts the 40- to 60-degree travel of the gate to a 240- to 360-degree travel of a 10-bit digital encoder, dividing gate motion into between 680 and 1,024 equal angular parts with an accuracy of plus-or-minus 1 bit (that is, from one part in 680 up to one part in 1,024, depending on the actual angular position of the gate).

The output of this encoder is converted into feet of vertical gate opening (h) by the site computer using gate geometry for calculation. The relationship is nonlinear, but an accuracy of at least one part in 300 is maintained even in the least accurate part of gate motion. This results in a measurement accurate to 0.1 foot for all radial gates by using the following equation.

$$h = H - R \sin\theta \left(1 - \frac{\text{encoder output at } h}{\text{encoder output at } h = H} \right)$$

where h = vertical gate opening (in feet)
H = height of gate arm trunnion above the invert
R = radius of the radial gate
θ = arc sin H/R

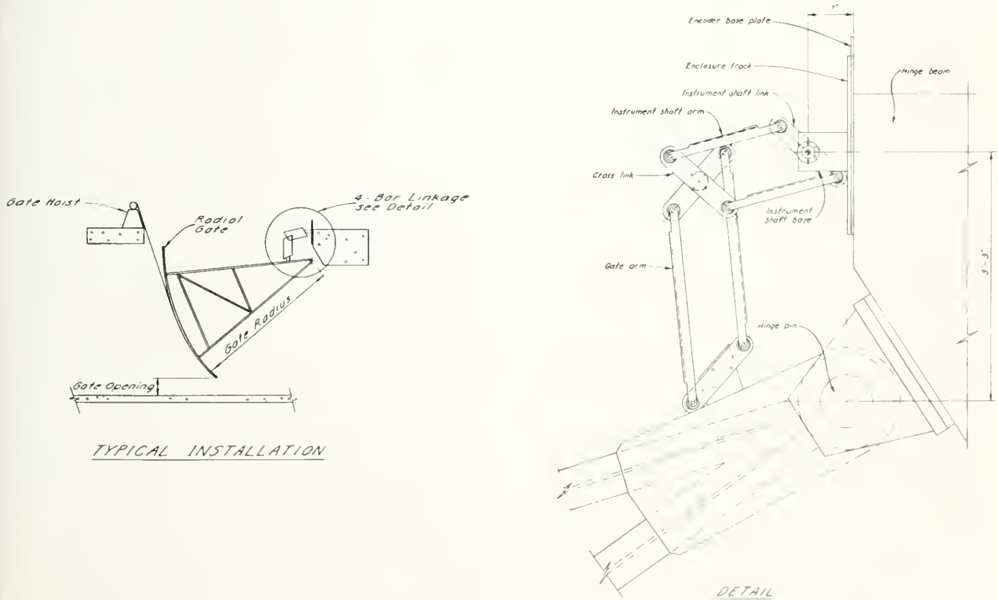


Figure 14. Four-Bar Linkage

Local, Automatic, Water-Level Control

Local, automatic, water-level controllers have been used for many years to control aqueducts which normally do not have any remote control. When used with proper respect for their limitations, they are successful in maintaining aqueduct water-level stability in the face of disturbances in the steady flow of water. They can automatically accommodate moderate changes in flow without endangering the Aqueduct due to water-level changes caused by flow mismatching. Such automatic adjustment is of real value when manual adjustment requires a water operator to go to each check structure to make the necessary manual adjustment.

The value of local, automatic, water-level control is less obvious when a remote control and monitoring system is available. In this case, an operator at the control center has the opportunity of observing water levels, being made aware of abnormal trends by alarms, and making the required adjustments rapidly from a control console.

It is only in an emergency, caused by failure of the remote control system to one or more of the check structures, that local, automatic, water-level controllers become useful. The original criteria for the aqueduct control system assumed that such control system failure would occur and that controllers would be able to moderate the effects of such failures. As a result of this, check structures No. 1 through No. 29 are provided with analog water-level controllers, which are interfaced to the check structure control equipment.

These controllers operate on a proportional plus reset algorithm,

$$d = K_1 e + K_2 T \int_0^T e\,dt$$

where d = change in gate position at time $t = T$ with respect to gate position at time $t = 0$

e = water level error (difference between water level and water-level setpoint at any time)

T = present time

K_1 and K_2 = constants based on the physical parameters of the individual sites.

Along with the automatic controllers, certain "bypass" hardware (which bypasses the computer system) is provided to communicate water level and other key alarm information back to the ACC in the event of a check structure computer failure.

Operating experience with early check structure controls showed that frequent failures of the computer never materialized. Failures do occur, but they are so infrequent that installation of the controllers was considered to be unnecessary. As a result of this experience, hardware local, automatic, water-level controllers were not included in subsequent designs (Check 31 and beyond).

To meet the automatic control requirements deemed necessary in the Operations Control Plan, provision for addition of a software water-level control program has been included in the check structure computer but, to date, its implementation has not been deemed necessary. Nevertheless, all features of hardware and system operation are present at all check structures so that local, automatic, water-level control can be implemented if required at some future time.

Since it was believed that reliability would be somewhat impaired by depending on one computer to serve both as the regular means of control (remote control) and as back-up means of control (local automatic control), the check structures south of No. 29 were provided with a second "hot-standby" computer. The second computer was actually installed only at a few structures for test purposes and has proven to be unnecessary because of the high reliability of the system with only one computer.

Subordinate Site Interface Equipment

In addition to check structures and plants, there are other functional structures along the Aqueduct. These additional structures are chiefly customer delivery points (turnouts) but also include flow measurement stations and water quality measurement stations. These structures generally have a small number of functions to be controlled or monitored remotely.

To have placed these structures directly on the control system communication line as major sites would have resulted in extra costs for the equipment required and increased the complexity of the communicaton line. Consequently, such structures were designated as "subordinate sites", and provisions were made to have them interface with the control system through check structure computers. The check structure computer provides encoding and decoding, memory, computation, and switching of messages between subordinate sites and the control center.

Commands for subordinate sites received from the control center are executed by the check structure computer through the subordinate site command interface. Interrogations of subordinate sites by the control center are responded to with data from the check structure computer memory. Memory locations containing this data are refreshed periodically by a scan of data at the subordinate sites through subordinate site data interface.

The check-site computers are provided with interfaces to communicate with subordinate sites by analog signals. The command interface included a digital-to-analog converter (DAC) and multiplexer for quantitative commands, such as setpoints.

The site computer, when it receives a setpoint command destined for a subordinate site, selects the correct site on the multiplexer and, through the DAC, produces a voltage corresponding to a full-scale "ready" signal followed by a voltage representing the command setpoint. These voltages are then sent to the subordinate site over telephone lines by use of frequency modulated (FM) tone transmitters. Nonquantized commands, such as "raise gate", are output by the check-site computer directly to a specified relay and transmitted to the subordinate site by a frequency-shift-keyed (FSK) tone transmitter dedicated to that function.

Data from subordinate sites are likewise received via FM and FSK tone receivers. If quantized, they are converted to a digital quantity by an analog-to-digital converter (ADC). Nonquantized data are passed on by relay outputs of the FSK receivers. Receiver outputs are present at all times and are scanned periodically by the check-site computer.

As a result of the inherent disadvantages of analog communications, and due to increasing availability and decreasing cost of digital equipment, the analog interface is not being used as extensively as originally planned. Instead, a digital interface is used, with the ADC and DAC located at the subordinate site.

Using this method, each check structure acts as a center in a radial communication system similar in many respects to the relationship of the check structures and the control center. Like the larger system, the check structure computer polls the subordinate sites with time-shared interrogations designating address and function and receives time-shared responses. The method of transmitting commands, time shared with the interrogations, and the provision of security for messages are also similar.

The most readily available digital interface, the 8-bit, serial, asynchronous interface of the check structure computer, is used to communicate with the subordinate sites.

Remote Monitoring and Control

Complete remote monitoring and control capability has been provided from the control center. This capability allows the operator in the remote control center to monitor and control the check structure in the same manner as can be done from the operator's panel at the site. Table 5 lists the functions that are exchanged.

Emergency Electrical Power

Electrical power at the check structures is obtained through utility company electrical service. For back-up purposes when the utility service fails, a liquefied petroleum gas (LPG)-fueled engine generator is provided at each check. Back-up power is fed through a transfer-switch arrangement, resulting in a short power interruption whenever a transfer is made. To enable satisfactory operation after such occurrences, power-failure reset and automatic restarting of all control equipment at the site are included as part of the system.

Table 5. Functions Monitored and Controlled at a Check Structure

COMMANDS
Select Manual Control
Select Automatic Control
Telephone Call Signal
Upstream Water Level Setpoint
Downstream Water Level Setpoint
Gate #1 Position Setpoint
Gate #2 Position Setpoint
Gate #3 Position Setpoint
Gate #4 Position Setpoint
DATA
Upstream Water Level Setpoint
Upstream Water Level
Downstream Water Level Setpoint
Downstream Water Level
Gate #1 Position Setpoint
Gate #1 Position
Gate #2 Position Setpoint
Gate #2 Position
Gate #3 Position Setpoint
Gate #3 Position
Gate #4 Position Setpoint
Gate #4 Position
STATUS
Automatic Control Mode
Manual Control Mode
Gate #1 Selected as Control Gate*
Gate #2 Selected as Control Gate*
Gate #3 Selected as Control Gate*
Gate #4 Selected as Control Gate*
Automatic Control from Upstream Setpoint
Automatic Control from Downstream Setpoint
Gate Speed No. 1 (slow)
Gate Speed No. 2 (medium)
Gate Speed No. 3 (fast)
Gate Speed No. 4 (emergency close)
ALARMS
Loss of Communications—Primary
Loss of Communications—Back-up
Primary Power Failure
Upstream Water Level High
Downstream Water Level High
Upstream Water Level Low
Downstream Water Level Low
Control Gate High Out-of-Range
Control Gate Low Out-of-Range
Unauthorized Building Entry
Failure of Gate No. 1†
Failure of Gate No. 2†
Failure of Gate No. 3†
Failure of Gate No. 4†
Computer Failure

* This status designates which gate will be modulated by the local automatic controller to maintain the selected setpoint. Selection is made locally.
† Failure of a gate is indicated when the gate position does not correspond to the gate position setpoint and the gate did not move at any time during a two-minute period.

Design of Pumping Plant Control Systems

Two basic philosophies exist in the department-designed pumping plant control systems, that is, computerized plants and noncomputerized plants. Although the techniques used to implement the control systems are dissimilar, the functional characteristics of each are alike.

The first level of control at all plants exists at the unit board. Here, individual units can be operated independently without regard to whether or not the plant control system is in operation. Unit board control is not considered to be a part of the plant control system (by definition).

The next level of control, the plant control system, consolidates control of all units, station service, switchyard, and plant auxiliaries from a central plant control room. It is the equipment in the plant control room that determines whether or not a plant is computerized.

Normally, units and plant equipment are operated from the operator's console in the plant control room.

In the following noncomputerized plants, control and monitoring are accomplished through hardwired equipment and do not make use of a plant computer.

Las Perillas Pumping Plant
Badger Hill Pumping Plant
South Bay Pumping Plant
Del Valle Pumping Plant

In the following computerized plants, a control computer performs the switching, translating, and computing functions required to monitor and control the plant.

Delta Pumping Plant
Buena Vista Pumping Plant
Wheeler Ridge Pumping Plant
Wind Gap Pumping Plant
A. D. Edmonston Pumping Plant
Oso Pumping Plant
Pearblossom Pumping Plant

All plants, whether they are computerized or not, have been designed with capability for, or have been adapted to, remote control and monitoring.

Plants with Conventional Controls

Department-designed plants with conventional (noncomputerized) controls are small in capacity compared to computerized plants, the largest being the Las Perillas and Badger Hill plants at 450 cubic feet per second capacity. They, and the South Bay and Del Valle Pumping Plants, have been designed without a plant control room per se, i.e., unit level control only (Figure 15).

The San Luis and Dos Amigos plant control systems, part of the joint-use facilities, were designed by the U.S. Bureau of Reclamation (References 5 and 6) and do not use a plant computer. They are, however, interfaced with the aqueduct control system for remote control by a small computerized system designed by the Department. These two plants use conventional controls with DC relays and other

Figure 15. Typical Unit Level Control Board

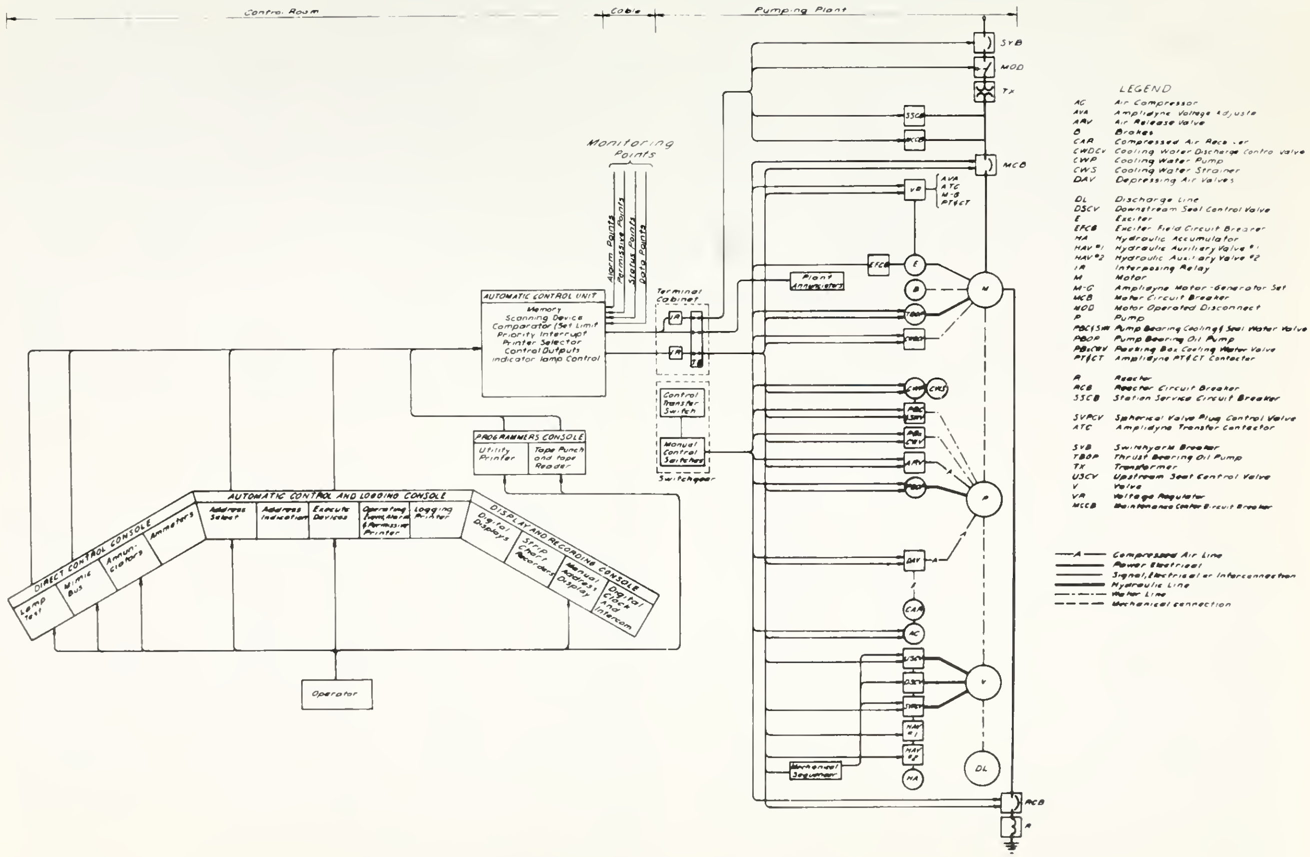


Figure 16. Functional Black Diagram—Delta Pumping Plant Control System

electromechanical devices. The central control console in the plant operates through these devices. Data displays are of the indicating or recording meter type. An events recorder prints out in numerical code alarms or status upon occurrence of changes, with summaries occurring periodically or upon request.

The computerized interface system employed at these two plants consists of a small (8K) computer interfaced to the plant and to the remote communication system. The function of the computer is to scan plant parameters and store data in memory for transmission to the remote control center. These plant parameters include both digital and analog inputs. The computers also respond to commands from a remote control center. These interface systems provide the same functional capability as the remote control interconnection at a plant with computerized controls. An exception to this is that no computer bypass capability exists at San Luis and Dos Amigos plants.

Las Perillas and Badger Hill Pumping Plants, on the other hand, are provided with remote control interconnection using hardware instead of a computer. This hardware is an enhanced version of the standard communications system which has been expanded to respond to additional command and data messages.

Plants with Computerized Controls

In a computerized plant, the computer is the interface between plant operator and plant equipment for the purposes of data monitoring and local control. In addition, the computer interfaces with the communication system for remote control and monitoring. A typical plant computer system consists of from 16K to 24K words of core memory, with from 32K to 96K words of secondary storage.

The functions of the computer can be grouped into categories of data monitoring, data display and recording, computation, control, and remote control interconnection.

All six of the computerized plants are similar in function, although control system hardware may be different. The Delta Pumping Plant was the first computerized plant in the Project and formed the basis from which other plant systems were designed. It is used as a typical plant control system.

Figure 16 is a functional block diagram of the Delta Pumping Plant control system. The computer used in the Delta plant system is a General Electric Model 4040.

Data Monitoring. Table 6 lists various functions that are monitored and controlled by the computerized plant system. These are pump points, motor points, valve points, transformer points, and miscellaneous plant points. There are three types of input signals from the plant equipment to the plant computer—interrupt, digital, and analog. Interrupt inputs are immediately answered by the computer and may cause certain control routines to be automatically executed. In addition, all points on interrupt are functionally identified and logged in their order of occurrence.

Both digital and analog inputs are scanned at periodic intervals by the plant computer. If the point is classified as an alarm, a change in state of the point will be annunciated both audibly and visually. The alarm also will be printed out over the alarm typewriter with the value of the off-normal condition included for analog inputs. Certain control routines may be initiated.

If the point is classified as a status point, the event is printed out and the change reflected on the mimic bus.

Data Display and Recording. Data are displayed or recorded on logging typewriters, digital displays, or analog chart records. All of the analog points as listed in column 6 of Table 6 are logged periodically. Points which belong to pumping units or major items of equipment not in use are not included in the logged parameters.

All alarm points and status points listed in column 3 of Table 6 are logged upon change in state. Analog points, and those calculated values which are designated as alarm points, are compared to preset limits and are logged as alarms if an out-of-limit condition is detected.

Certain special logging features are available to the operator on demand. These consist of summary printouts of points currently in the alarm state (active alarms); group review logs which are arranged so the operator may initiate a printout of all analog inputs for any major piece of equipment; or a printout of all analog inputs on a functional basis such as temperatures, pressures, flows, and so forth.

The computer also provides a log at the completion of unit start-up and prior to unit shutdown on demand by the operator. An operator can log any point or group of points on demand.

The computer provides the capability to display up to six points on digital displays or to record (trend) up to six points on a series of analog strip-chart recorders.

Computation. The computer provides the computational capability necessary to scale all data monitored. In addition, certain variables, such as motor field temperatures, are calculated from other inputs available to the computer.

Control. The computer provides for control of the plant either through the plant console or remotely for complete unit start-up or shutdown. On a complete computer start-up, as an example, the computer performs all the necessary permissive checks prior to start-up, starts the unit auxiliaries, depresses the water level in the pump, closes the unit breaker, monitors the unit starting, waters the pump, and opens the discharge valve.

Table 6. Functions Monitored and Controlled at a Typical Computerized Pumping Plant—continued

Column No.	KEY
1	ASA Device No.
2	Description of Point
3	Instrumentation Points (Inputs) AP — Alarm Point PP — Permissive Point SP — Status Point (Operating Events) DP — Data Point
4	Control Points (Outputs) S — Start or Stop Routine Point W — Direct-Wired Point
5	Scan Period/Interrupt Point (INT)
6	Periodically Logged
7	Shutdown Point NORM — Normal Shutdown EMERG — Emergency Shutdown

1	2	3				4	5	6	7
		AP	PP	SP	DP				
	PUMP POINTS								
38B	Pump Bearing Temperature	X	—	—	X	—	15S	X	NORM
38H	Pump Bearing Hot-Spot Temperature	X	—	—	—	—	5S	—	NORM
38P	Packing Box Temperature	X	—	—	—	—	5S	—	NORM
63R	Pump Bearing Low Oil Level	X	X	—	—	—	5S	—	NORM
63RH	Pump Bearing High Oil Level	X	—	—	—	—	5S	—	NORM
63A	Packing Box Cooling Water Pressure	X	X	—	X	—	15S	X	NORM
63E	Pump Bearing Oil Pressure	X	X	—	X	—	15S	X	NORM
63G	Pump Bearing Cooling Water Pressure	X	X	—	X	—	15S	X	NORM
63ZU	Upper Seal Water Pressure	—	X	—	—	—	—	—	—
63ZL	Lower Seal Water Pressure	—	X	—	—	—	—	—	—
63K	Pump Bowl Water Level	—	X	—	—	—	—	—	—
220G	Open Pump Bearing Cooling and Seal Water Valve	—	—	—	—	S	—	—	—
220H	Close Pump Bearing Cooling and Seal Water Valve	—	—	—	—	S	—	—	—
220J	Open Packing Box Cooling Water Valve	—	—	—	—	S	—	—	—
220K	Close Packing Box Cooling Water Valve	—	—	—	—	S	—	—	—
204E	Start Pump Bearing Oil Pump	—	—	—	—	S	—	—	—
204F	Stop Pump Bearing Oil Pump	—	—	—	—	S	—	—	—
220L	Open Water Depressing Air Valves	—	—	—	—	S	—	—	—
220M	Close Water Depressing Air Valves	—	—	—	—	S	—	—	—
220P	Open Air Release Valve	—	—	—	—	S	—	—	—
220R	Close Air Release Valve	—	—	—	—	S	—	—	—
33T	Air Release Valve Position	—	X	—	—	—	—	—	—
	MOTOR POINTS								
12	Reverse Overspeed	X	—	—	—	—	1S	—	EMERG
26	Amortisseur Temperature	X	—	—	—	—	1S	—	EMERG
99A	Field Current	—	—	—	X	—	—	X	—
99B	Field Voltage	—	—	—	X	—	—	X	—
26F	Field Temperature	X	—	—	X	—	15S	X	NORM
26L	Lower Guide Bearing Oil Temperature	X	—	—	—	—	5S	—	NORM
26C	Motor Cooling Air Exhaust Temperature	X	—	—	X	—	15S	—	NORM
26M	Motor Cooling Air Exhaust Temperature	X	—	—	—	—	5S	—	NORM
26T	Thrust and Upper Guide Bearings Oil Temperature	X	—	—	—	—	5S	—	NORM
38K	Lower Guide Bearing Temperature	X	—	—	—	—	5S	—	NORM
38L	Lower Guide Bearing Temperature	X	—	—	X	—	15S	X	NORM
38J	Thrust Bearing Temperature	X	—	—	—	—	5S	—	NORM
38T	Thrust Bearing Temperature	X	—	—	X	—	15S	X	NORM
38U	Upper Guide Bearing Temperature	X	—	—	X	—	15S	X	NORM
38V	Upper Guide Bearing Temperature	X	—	—	—	—	5S	—	NORM
46	Negative Phase Sequence Current	X	—	—	—	—	INT	—	EMERG
48	Incomplete Starting Sequence	X	—	—	—	—	INT	—	EMERG
49S	Stator Temperature	X	—	—	—	—	1S	—	NORM
49S	Stator Temperature	X	—	—	X	—	15S	X	NORM
51V	Time Overcurrent	X	—	—	—	—	INT	—	EMERG
53	Field Failure	X	—	—	—	—	INT	—	EMERG
55	Loss of Synchronism	X	—	—	—	—	INT	—	EMERG
59	Neutral Overvoltage	X	—	—	—	—	INT	—	EMERG
63	Thrust Bearing Oil Level	X	X	—	—	—	5S	—	NORM
63P	Motor Bearing Cooling Water Pressure	X	X	—	—	—	5S	—	NORM
64F	Field Ground	X	—	—	—	—	INT	—	EMERG

Table 6. Functions Monitored and Controlled at a Typical Computerized Pumping Plant—continued

1	2	3				4	5	6	7
		AP	PP	SP	DP				
	MOTOR POINTS—Continued								
86M	Motor Lockout Relay Position	X	X	—	—	—	INT	—	EMERG
87M	Differential Current	X	—	—	—	—	INT	—	EMERG
43R	Regulator Switch Position	—	X	—	—	—	—	—	—
98A	Indication of Synchronization	—	X	—	—	—	—	—	—
99C	Line Current	—	—	—	X	—	—	X	—
99D	Line Voltage	—	—	—	X	—	—	X	—
63C	Air Cooler Water Pressure	X	X	—	—	—	5S	—	NORM
99E	Kilowatts	—	—	—	X	—	—	X	—
99F	Kilovars	X	—	—	X	—	15S	X	—
63M	CO_2 Release	X	—	—	—	—	5S	—	EMERG
14	Unit Run Switch	—	—	X	—	—	INT	—	—
220A	Release Motor Cooling Water Discharge Control Valve	—	—	—	—	S	—	—	—
220B	Close Motor Cooling Water Discharge Control Valve	—	—	—	—	S	—	—	—
204A	Start Thrust Bearing Oil Pump	—	—	—	—	S	—	—	—
204B	Stop Thrust Bearing Oil Pump	—	—	—	—	S	—	—	—
252A	Close Motor Breaker	—	—	—	—	S	—	—	—
252B	Open Motor Breaker	—	—	—	—	S	—	—	—
63T	Thrust Bearing High Oil Pressure	—	X	—	—	—	—	—	—
33A	Brake Position	—	X	—	—	—	—	—	—
33B	Motor Breaker Assembly Position	—	X	—	—	—	—	—	—
33C	Motor Breaker Position	—	X	X	—	—	INT	—	—
33D	Exciter Field Breaker Position	—	X	X	—	—	INT	—	—
33E	Reactor Breaker Position	—	X	X	—	—	INT	—	—
204C	Close Reactor Breaker	—	—	—	—	S	—	—	—
204D	Open Reactor Breaker	—	—	—	—	S	—	—	—
	VALVE POINTS								
63V	Hydraulic System Pressure	X	X	—	—	—	5S	—	—
63L	Accumulator Oil Level	X	X	—	—	—	5S	—	—
63S	Hydraulic Sump Level	X	—	—	—	—	5S	—	—
33F	Spherical Valve Plug Position (Open)	—	X	X	—	—	—	—	—
33F	Spherical Valve Plug Position (Closed)	—	X	X	—	—	—	—	—
33G	Downstream Seat Position	—	X	—	—	—	—	—	—
33H	Upstream Seat Position	—	X	—	—	—	—	—	—
63W	Discharge Pressure	—	X	—	—	—	—	—	—
220U	Energize Upstream Seat Control Valve	—	—	—	—	S	—	—	—
220V	De-energize Upstream Seat Control Valve	—	—	—	—	S	—	—	—
220W	Energize Spherical Valve Plug Control Valve	—	—	—	—	S	—	—	—
220X	De-energize Spherical Valve Plug Control Valve	—	—	—	—	S	—	—	—
43B	Mechanical Sequencer Selector Switch Position	—	X	—	—	—	—	—	—
204T	Advance Mechanical Sequencer	—	—	—	—	S	—	—	—
204U	Reverse Mechanical Sequencer	—	—	—	—	S	—	—	—
33V	Mechanical Sequence Complete (Adv.)	—	X	—	—	—	—	—	—
33W	Mechanical Sequence Complete (Rev.)	—	X	—	—	—	—	—	—
33U	Hydraulic Auxiliary Valves Position	—	X	—	—	—	—	—	—
	TRANSFORMER POINTS								
26R	Transformer Cooling Oil Temperature	X	—	—	—	—	5S	—	NORM
49R	Transformer Winding Hot Spot Temperature	X	—	—	—	—	5S	—	NORM
49T	Transformer Winding Temperature	X	—	—	X	—	10S	X	NORM
51G	Transformer Neutral Overcurrent	X	—	—	—	—	INT	—	EMERG
63D	Transformer Sudden Pressure	X	—	—	—	—	INT	—	EMERG
63J	Transformer Cooling Oil Level	X	—	—	—	—	5S	—	NORM
86T	Transformer Lockout Relay	X	—	—	—	—	INT	—	EMERG
87T	Transformer Differential Current	X	—	—	—	—	INT	—	EMERG
63H	Transformer Pressure	X	—	—	—	—	5S	—	NORM
47	Undervoltage and Phase Sequence	X	X	—	—	—	INT	—	EMERG
63EE	Transformer Water Spray Released	X	—	—	—	—	INT	—	EMERG

Table 6. Functions Monitored and Controlled at a Typical Computerized Pumping Plant—continued

1	2	3				4	5	6	7
		AP	PP	SP	DP				
	MISCELLANEOUS POINTS								
71L	Intake Channel Water Level	X	X	—	X		INT	X	NORM
33J	Plant DC Voltage	X	X	—	—	—	5S	—	EMERG
33K	Control Room DC Voltage	X	—	—	—	—	5S	—	—
16A	Plant Battery Charger Failure	X	—	—	—	—	5S	—	—
16B	Control Room Battery Charger Failure	X	—	—	—	—	5S	—	—
64A	Plant Battery Ground	X	—	—	—	—	5S	—	—
64B	Control Room Battery Ground	X	—	—	—	—	5S	—	—
27A	Oil Room CO_2 System Voltage	X	—	—	—	—	5S	—	—
50/51	Station Service Overcurrent	X	—	—	—	—	INT	—	
99G	Station Service Kilowatts	—	—	—	X	—	—	X	
99H	Plant Kilowatt Hours	—	—	—	X	—	—	—	—
63N	Plant Air Pressure	X	X	—	—	—	5S	—	—
63U	Sump Water Level	X	—	—	—	—	5S	—	—
63F	Water Flow	—	—	—	X	—	—	X	—
63Y	Total Water Delivered	—	—	—	X	—	—	X	—
26B	Oil Storage Room Fire	X	—	—	—	—	INT	—	—
86S	Station Service Lockout	X	—	—	—	—	INT	—	
30HV	Heating and Air Conditioning	X	—	—	—	—	5S	—	—
87B	Bus Differential Current	X	—	—	—	—	INT	—	EMERG
99J	Reactive Volt-Amperes (Plant)	—	—	—	X	—	—	X	—
99K	Voltage (Plant) (230 kV)	—	—	—	X	—	—	X	—
51G	Station Service Ground	X	—	—	—	—	5S	—	—
63X	Cooling Water Pump Pressure	X	X	—	—	—	15S	—	NORM
204BB	Energize Amplidyne Transfer Contactor	—	—	—	—	S	—	—	—
204V	De-energize Amplidyne Transfer Contactor	—	—	—	—	S	—	—	—
204Z	Energize Amplidyne PT and CT Contactor	—	—	—	—	S	—	—	
204W	De-energize Amplidyne PT and CT Contactor	—	—	—	—	S	—	—	—
204G	Start Cooling Water Pump and Strainer	—	—	—	—	S	—	—	—
204H	Stop Cooling Water Pump and Strainer	—	—	—	—	S	—	—	
204K	Close Switchyard Breaker	—	—	—	—	W	—	—	—
204L	Open Switchyard Breaker	—	—	—	—	W	—	—	—
204N	Close Station Service 13.8 kV Breaker	—	—	—	—	W	—		—
204P	Open Station Service 13.8 kV Breaker	—	—	—	—	W	—	—	—
224A	Close Motor-Operated Disconnect Switch	—	—	—	—	W	—	—	—
224B	Open Motor-Operated Disconnect Switch	—	—	—	—	W	—	—	—
33P	Switchyard Breaker Position	—	—	X	—	—	INT	—	—
33R	Station Service 13.8 kV Breaker Position	—	—	X	—	—	INT	—	—
33S	Motor-Operated Disconnect Switch Position (Open)	—	—	X	—	—	INT	—	—
33Z	Motor-Operated Disconnect Switch Position (Close)	—	—	X	—	—	INT	—	—
43T	Control Transfer Switch Position	X	X	—	—	—	INT	—	—
204J	Start 375 CFM Air Compressors	—	—	—	—	S	—	—	—
204S	Stop 375 CFM Air Compressors	—	—	—	—	S	—	—	—
33X	Radial Gate Position	—	X	—	—	—	—	—	—
204X	Start Amplidyne M-G Set	—	—	—	—	S	—	—	—
204Y	Stop Amplidyne M-G Set	—	—	—	—	S	—	—	
13B	M-G Set Speed	—	X	—	—	—	—	—	—
33M	Amplidyne PT and CT Contactor Position	—	X	—	—	—	—		
99L	Amplidyne Voltage	—	X	—	—	—	—	—	—
204AA	Operate Amplidyne Voltage Adjuster	—	—	—	—	S	—		
33Y	Amplidyne Transfer Contactor Position	—	X	—	—	—	—		
27M	Unit DC Voltage	X	X	—	—	—	5S	—	EMERG
	375 CFM Air Compressor Status	—	X	—	—	—	—	—	—
27T	Bay DC Voltage	X	X	—	—	—	5S	—	EMERG
63AA	Air Compressor Cooling Water Pressure	X	—	—	—	—	5S	—	—

The operator can also request a partial unit start to verify proper unit permissives and unit auxiliary operation prior to the need to perform a complete start-up.

Normal shutdown of a unit can be accomplished either by the operator through the plant console, from a remote stop command, as a result of internal action on an alarm point which is not aborted by the operator, or as a result of an aborted unit start-up which requires a return to the shutdown state.

When an emergency shutdown occurs, it usually results from the unit's protective relaying or by direct trip either by the operator or remotely. The motor breaker is tripped and the main discharge valve is automatically closed by equipment external to the control system. The computer automatically provides back-up to this external equipment to shut down the auxiliary equipment of the tripped unit(s).

Direct-wire control (bypassing the computer) exists for certain critical functions at the plant. These controls are as follows:

1. Open and close each motor-operated disconnect.
2. Open and close each switchyard circuit breaker.
3. Open and close each station service high-voltage breaker and maintenance yard feeder high-voltage breaker.
4. Reset and silence all annunciators and alarms located in the control room and plant.
5. Emergency trip each motor circuit breaker.

Operator communication with the control system is through the operator's console shown in Figure 17. This console provides a mimic panel (Figure 18) depicting the plant single-line diagram, with direct-wire controls installed. The console also contains various thumb wheel switches and pushbuttons (Figure 19) through which the operator communicates with the computer. Finally, the logging typewriters, digital displays, and analog recorders are contained in the console. Figure 20 shows the digital displays and analog recorders.

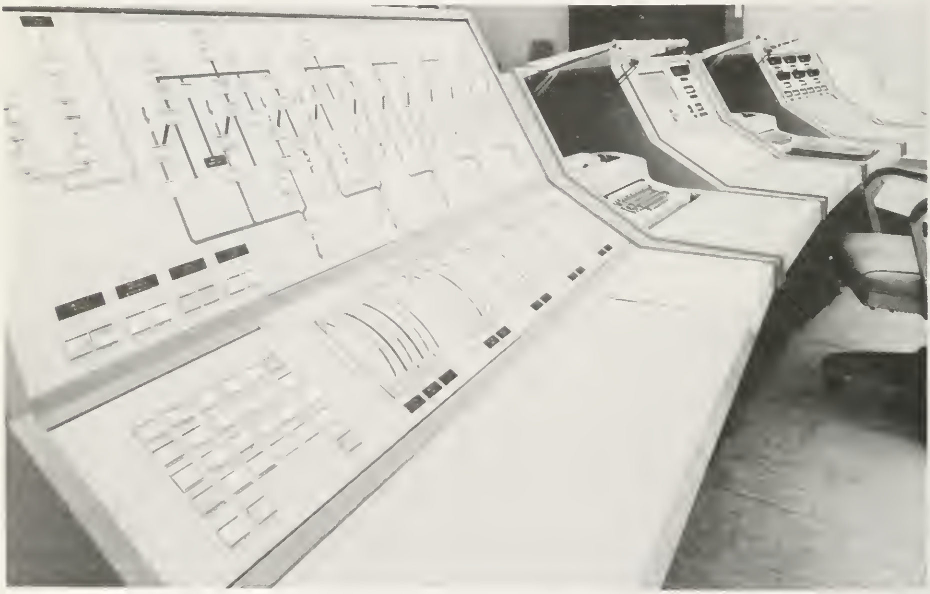


Figure 17. Operator's Console—Delta Pumping Plant Control System

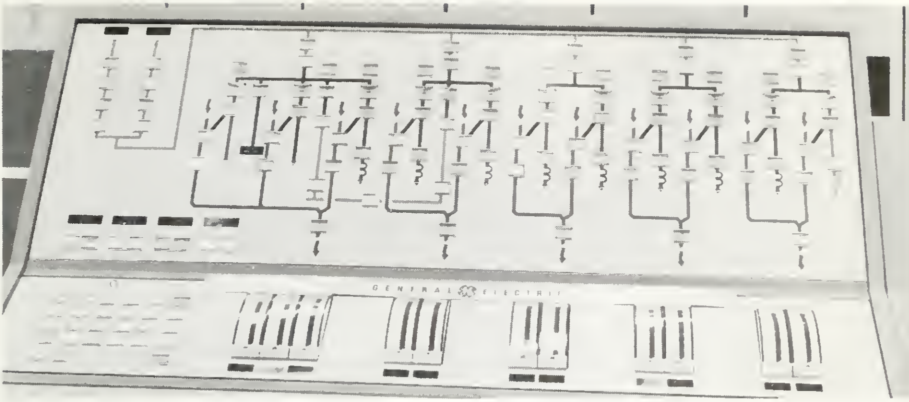


Figure 18. Mimic Panel—Delta Pumping Plant Control System

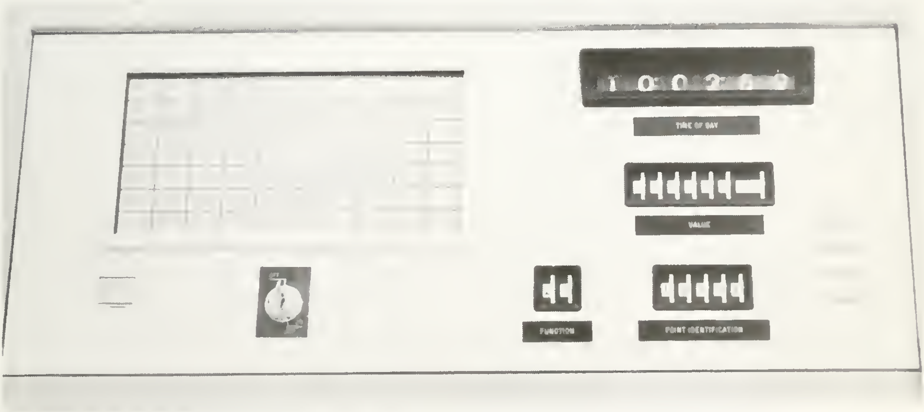


Figure 19. Operator Communication—Delta Pumping Plant Control System

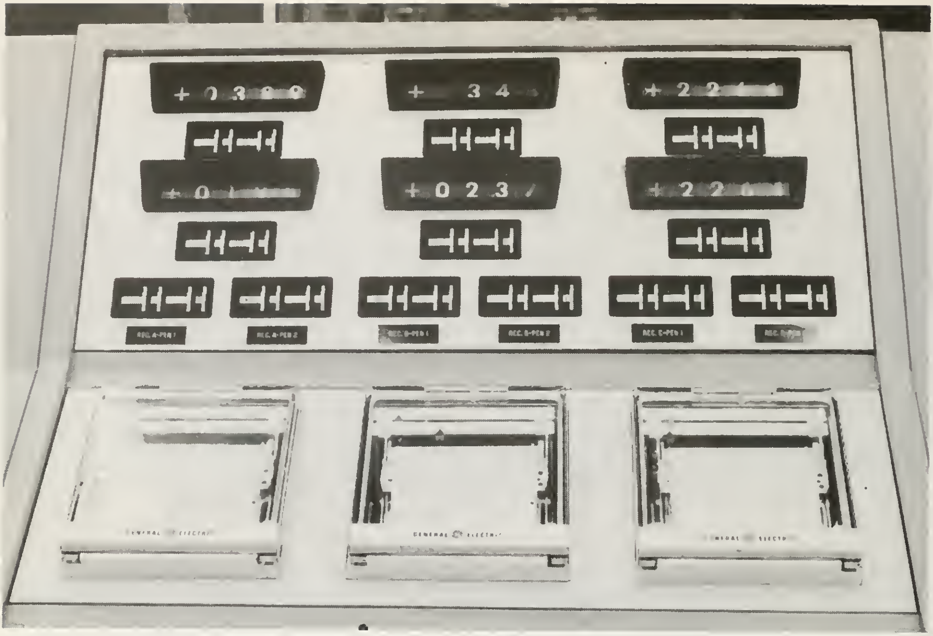


Figure 20. Digital Displays and Analog Recorders—Delta Pumping Plant Control System

Remote Control Interconnection. Control and monitoring of plants at the plant control room provides for a larger number of points to be available at the plant control console and for frequent updating of monitored variables. When control is exercised from a remote location, such as the ACC or the POCC, practical considerations require a reduction in the number of points monitored, in the frequency of updating, and in the variety of controls available. To transmit plant data back to the ACC would result in a communications requirement significantly greater than the capacity of the lines used on the aqueduct system.

Pumping plants can be operated remotely with much less data than are required at the plant itself. Table 7 shows the command, data, and status information exchanged between the remote control center and the plant system.

Alarms transmitted from the plant to the remote control center convey less detailed information than is available at the plant control room. The concept of remote control of a plant is one of dispatch rather than supervisory control. The primary concern of the operator in the remote control center is whether or not a unit is available for service. Since the units and other features of the plant are protected from damage by local protective devices, the quantity of alarm information transmitted remotely is held to a minimum. Plant and unit alarms are grouped by function, and it is the general alarm which is transmitted remotely. Table 8 lists the alarms which are transmitted to the ACC.

Table 7. Information Exchanged Between an ACC and a Typical Pumping Plant System

COMMANDS
Start Unit—Each unit
Stop Unit (normal)—Each unit
Stop Unit (emergency)—Each unit
Open Breaker—Each switchyard breaker
Close Breaker—Each switchyard breaker
DATA
Intake Water Level
Penstock Flow (cfs)—Each penstock
Line Voltage—Each transmission line
Megawatts—Each transmission line
Vars—Each transmission line
Unit Megawatts—Each unit
Unit Vars—Each unit
Plant Power Demand
STATUS
Status of the Headworks Gates; open, closed
Status of the Switchyard Breakers; open, closed
Unit I/S (In-Service)
Unit S/D (Shutdown)
Unit O/S (Out-of-Service)

Remote communication is handled by a standard communication system which is interfaced to the plant computer. In addition, this communication equipment provides a computer bypass capability for remote emergency shutdown of the pumping units. To accomplish this bypass function, communication terminal equipment has been enhanced to provide site code recognition and checking of the message security code (parity). It also "gates" command signals to the proper plant control contacts. This bypass feature is provided to allow emergency shutdown of the units when the plant computer is out of service.

Table 8. Alarms Transmitted Between a Typical Pumping Plant System and the ACC

ALARM WHICH IS TRANSMITTED REMOTELY	PLANT CONDITION WHICH CAUSES ALARM TO BE SENT
Plant Alarms	
Plant Local Control	ACC Lockout Set
Primary Power Fail	PG&E Load Shed Relay
Plant Warning	Station Service Lockout
	Oil Storage Room Fire
	Forebay Water Level High
	Plant Air Pressure
	Sump Water Level High
	Bay DC Voltage
	Air Compressor Cooling Water Pressure
	Switchyard DC Failure
Bus Differential	230 kV Bus Differential
Switchyard Breaker	Line Distance Relay
Trip (Each Breaker)	Carrier Distance Ground
	Breaker SF_6 High Pressure
	Overcurrent
	Carrier Operate
PG&E Undervoltage	PG&E Undervoltage
Transformer Lockout (Each Transformer)	Transformer Lockout
Transformer Trouble (Each Transformer)	Oil Temperature
	Hot Spot
	Hot Spot Trip
	Winding Temperature
	Neutral Current
	Fault Pressure
	Water Spray
	Pressure Relief
	Differential Current
	Oil Level
	Undervoltage
Unit Alarms (Each Unit)	
Pump Temperature	Pump Bearing Temperature
	Intermediate Bearing Temperature
	Packing Box Temperature
Unit Lockout	Motor Breaker Tripped & Locked Out
Motor Temperature	Lower Guide Bearing Oil Temperature
	Lower Guide Bearing Temperature
	Upper Guide Bearing Temperature
	Thrust Bearing Temperature
	Thrust & Upper Guide Bearing Oil Temperature
	Motor Cooling Air Exhaust Temperature
	Motor Bearing Cooling Water Pressure
	Stator Temperature
	Air Cooler Water Pressure
Reverse Overspeed	Reverse Overspeed
Electrical Fault	Negative Phase Sequence
	Time Overcurrent
	Field Failure
	Loss of Synchronism
	Neutral Overvoltage
	Field Ground
	Differential Current
CO_2 Discharge	CO_2 Discharge
Start Failure	Incomplete Sequence
Unit Warning	Unit DC Voltage
	Discharge Valve Downstream Seat Position
	Thrust Bearing Oil Level
	Pump Bearing Oil Level
	Hydraulic System Pressure
	Accumulator Oil Level

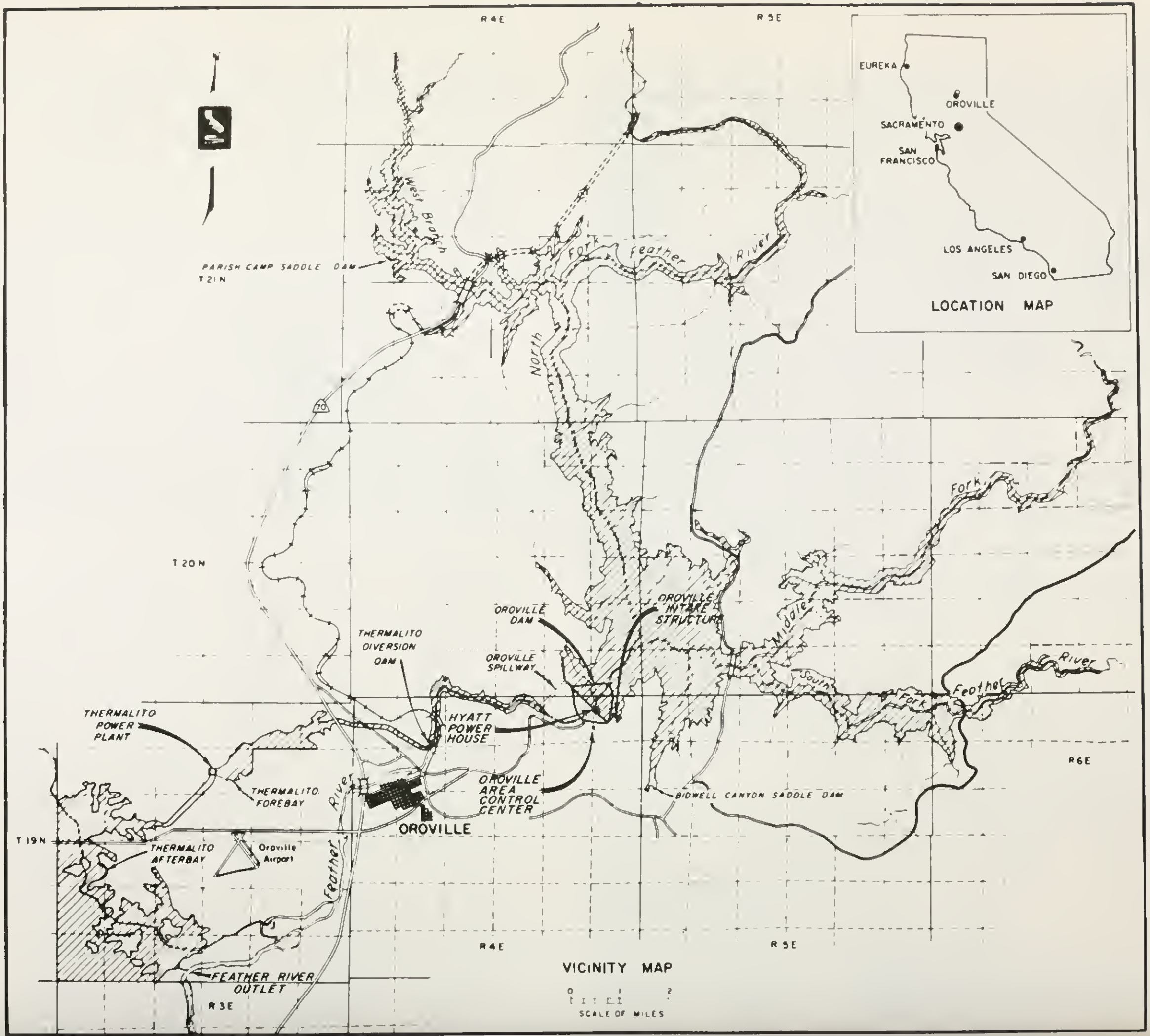


Figure 21. Location of the Oroville-Thermalito Facilities

Design of Power Plant Control Systems

Two power plant control systems have been designed by the Department, the Oroville-Thermalito system and the Devil Canyon system.

Oroville-Thermalito Control System

The Oroville-Thermalito control system provides remote supervisory control, automatic load-control, and data acquisition for Edward Hyatt and Thermalito Powerplants, Oroville Switchyard, 11 hydraulic structures, and 12 gauging stations.

The Oroville-Thermalito control system includes equipment in Edward Hyatt Powerplant, Thermalito Powerplant, and associated hydraulic structures, as well as necessary connecting lines. Figure 21 shows the location of the Oroville-Thermalito facilities.

Edward Hyatt Powerplant is located underground, beneath the left abutment of Oroville Dam. The Oroville Control Building is located aboveground, next to Oroville Switchyard and approximately 2,000 feet from Edward Hyatt Powerplant.

All features of Thermalito Powerplant are located aboveground, approximately 8 miles from the Oroville ACC.

The Oroville-Thermalito control system is normally operated from the Oroville ACC (Figure 22) but, in the event of an emergency, operation is possible from an emergency control room located in the underground Edward Hyatt Powerplant.

The Oroville-Thermalito control system is composed of three supervisory subsystems, three telemetry subsystems, a data logging subsystem, an alarm events and status change subsystem, and an automatic load-control subsystem. Figure 23 is a block diagram of the Oroville-Thermalito control system.

Supervisory Subsystems. Three supervisory subsystems are provided for remote control of, and selected data acquisition from, unattended facilities of the Oroville-Thermalito power complex.

One subsystem is assigned to Edward Hyatt Powerplant and one gauging station. This subsystem is activated from its master station in the Oroville ACC. Commands are executed and data collected by the remote station located in Edward Hyatt Powerplant. Figure 24 shows the master station console.

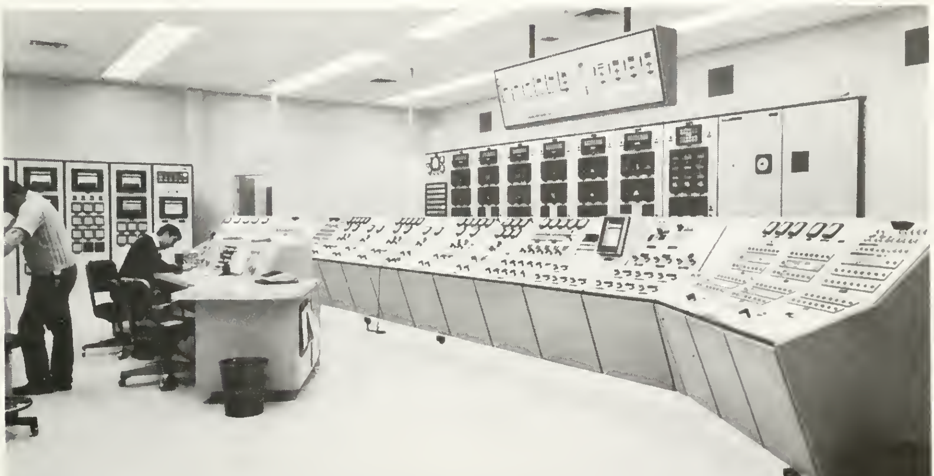


Figure 22. Oroville Area Control Center

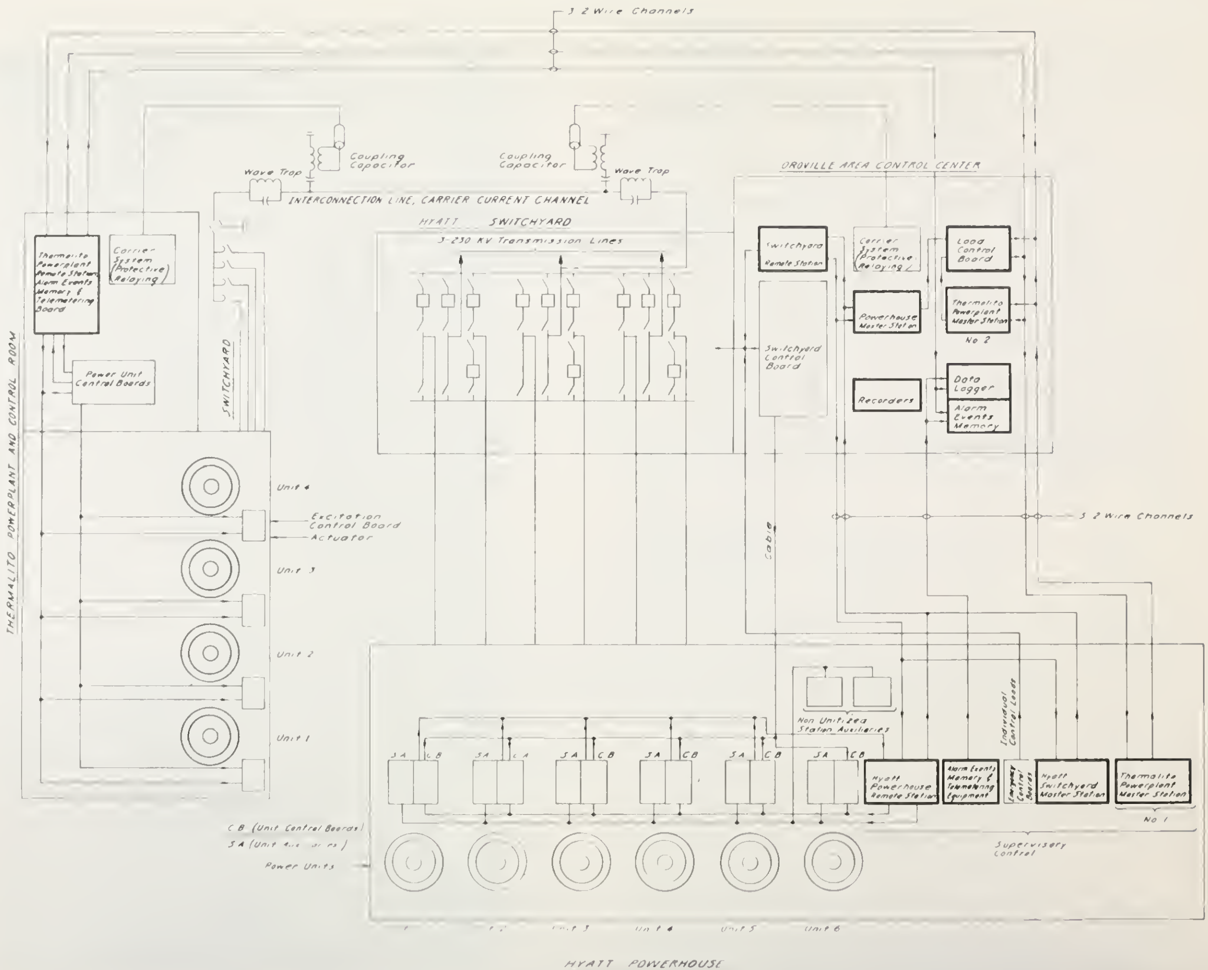


Figure 23. Functional Block Diagram—Oroville-Thermalito Control System

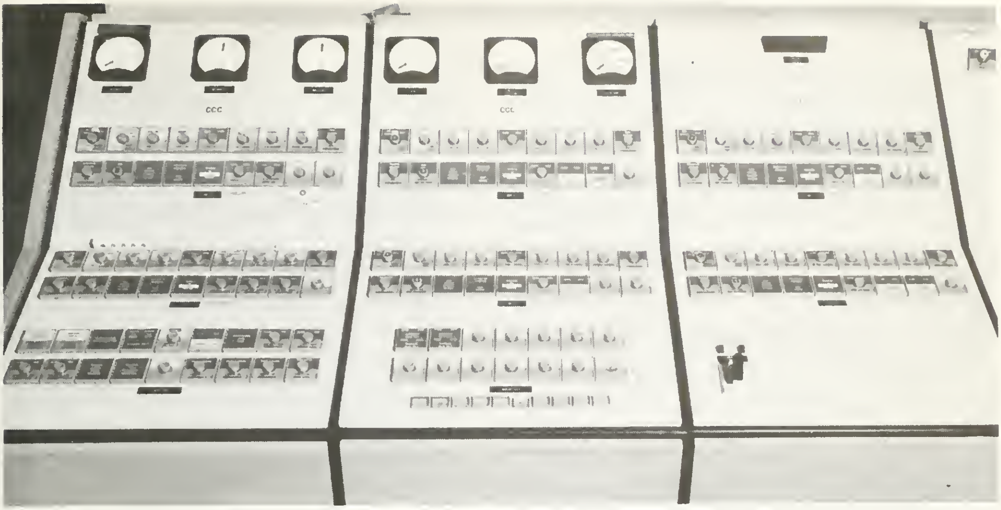


Figure 24. Master Console—Edward Hyatt Powerplant Supervisory Subsystem

The second subsystem is assigned to Thermalito Powerplant, six hydraulic structures, and five gauging stations. This subsystem can be activated from either of two master stations, one of which is in the Oroville ACC and the other in the emergency control room in Edward Hyatt Powerplant. Commands for the second subsystem are executed and data collected by a remote station located at Thermalito Powerplant and remote stations at the associated hydraulic structures. Figure 25 shows the master station at the ACC.

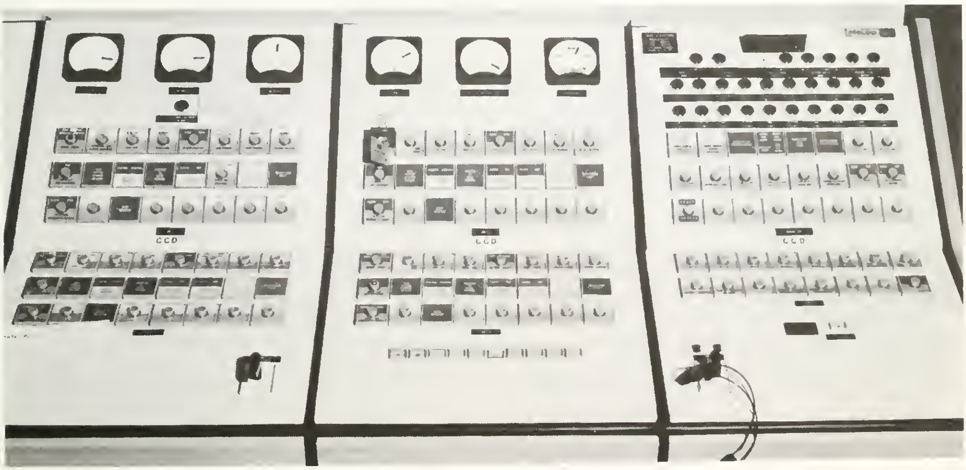


Figure 25. Master Console—Thermalito Powerplant Supervisory Subsystem

The third subsystem is assigned to Oroville Switchyard, five hydraulic structures, and six gauging stations. This subsystem is activated from its master station in the emergency control room of Edward Hyatt Powerplant. Figure 26 shows this master console. Associated hydraulic structures can also be activated from the hydraulic structures master station (Figure 27) located in the Oroville ACC. Commands for the third subsystem are executed and data collected by the remote station located in the Oroville ACC and remote stations at associated hydraulic structures.

Hydraulic structures and gauging stations of the Oroville-Thermalito power complex, which are controlled and monitored through three supervisory subsystems, are located in the vicinity of Oroville Dam, on the Feather River between Oroville Dam and Thermalito Powerplant, and around Thermalito Forebay and Afterbay.

The Oroville Dam core block gauging station is controlled through the Edward Hyatt Powerplant supervisory subsystem. Features near Oroville Dam and on the Feather River are controlled through the Oroville Switchyard supervisory subsystem. Features around Thermalito Forebay and Afterbay are controlled through the Thermalito Powerplant supervisory subsystem. The telemetered variables are hydraulic in nature and are displayed in digital form at appropriate master stations.

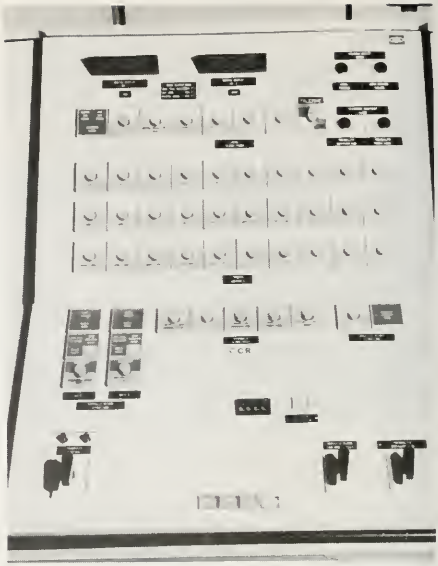


Figure 27. Hydraulic Structure Master Console—Oroville Switchyard Supervisory Subsystem

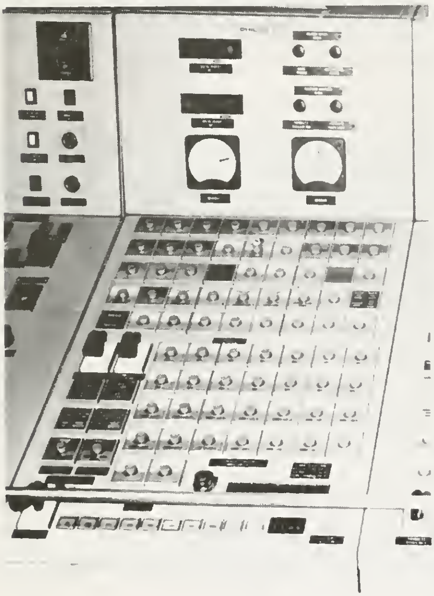


Figure 26. Master Console—Oroville Switchyard Supervisory Subsystem

There are four small computers (all are Digital Equipment Corporation Model DPD-8/S) in the three supervisory subsystems, one computer being installed in each of the four master stations. One computer is installed in the Edward Hyatt Powerplant master console and is assigned to that subsystem. The second computer is installed in the Oroville Switchyard master console and is assigned to that subsystem. The third and fourth computers, assigned to the Thermalito Powerplant subsystem, are installed in two separate master consoles. One, installed in the Thermalito Powerplant master console, is located in the emergency control room. The other, installed in the hydraulic structures master console in the Oroville ACC, is assigned not only to the Thermalito Powerplant subsystem but also to hydraulic structures of the Oroville Switchyard subsystem.

The following tables summarize the control and monitoring capability through the Edward Hyatt Powerplant, Thermalito Powerplant, and Oroville Switchyard supervisory subsystems.

The points in each subsystem that pertain to a single pumping unit or other piece of apparatus are designated as "unitized". The points in each subsystem that are related to all units or apparatus are designated as "nonunitized".

Table 9 shows capabilities through the Edward Hyatt Powerplant supervisory subsystem. Table 10 shows capabilities through the Thermalito Powerplant supervisory subsystem. The capabilities through the Oroville Switchyard subsystem are shown in Table 11.

Table 9. Supervisory Capability—Edward Hyatt Powerplant

TYPE	IDENTIFICATION	COMMAND AND STATUS	UNIT-IZED	NON-UNIT-IZED
CI	Master Control	Start/Stop/Check—Start Sequence—Complete/Unit	X	—
CI	Condenser Programming*	ON/OFF—Cond/Gen/Reduced Freq	X	—
C	Load Limit (Wicket Gate Limit)	Raise/Lower/Check	X	—
C	Speed Level	Raise/Lower/Check	X	—
CI	Bypass Dashpot	Open/Close—Close/Open	X	—
C	Field Rheostat	Raise/Lower/Check	X	—
C	Voltage Adjuster	Raise/Lower/Check	X	—
CI	Auto Synchronizer†	ON/OFF—Main Breaker	X	—
CI	Emergency Unit Shutdown	Trip and Annunication	X	—
I	Partial Shutdown	Unit Tripped to Speed No Load	X	—
I	Shutdown	Incomplete Sequence/Unit Creeps	X	—
I	Transfer to Local Control	Local Control	X	—
CI	Penstock Valve	Open/Close—Close/Open	X	—
CI	15 kV Disconnect Switch Generator‡	Open/Close—Close/Open	X	—
CI	Load Control	Local Manual/Auto Control	X	—
CI	Auto Synchronizer	ON/OFF—Main Breaker	X	—
I	15 kV Disconnect Switch Pump§	Close/Open	X	—
I	Mode Orientation	Blocking Gen—Pwr Complex/Gen	—	X
I	Mode Orientation	Blocking Pumping—Pwr Complex/Pumping	—	X
I	Master Station Control	Master Station—Xfer Control	—	X
I	Xfer to Emergency Generator	Xfer to Emergency Generator	—	X
CI	Core Block Sump Pump No. 1	Pump Running—Start/Stop	—	X
CI	Core Block Sump Pump No. 2	Pump Running—Start/Stop	—	X
CI	Core Block Sump Pump No. 3	Pump Running—Start/Stop	—	X
CI	Core Block Water Level	High Water Level—Water Level	—	X
I	Master Check	Master TLM, Remote TLM, and Command Errors	—	X
I	Breaker UIB	Close/Trip	—	X
I	Powerplant Gate Lock	Close/Trip	—	X
CI	Station Service P3A1	Close/Trip	—	X
CI	Station Service P3A2	Close/Trip	—	X
CI	Station Service P4A1	Close/Trip	—	X
CI	Station Service P4A2	Close/Trip	—	X
CI	Station Service Pwr Xfer	Close/Trip	—	X
I	Spherical and Dispersion Valves No. 1	Close/Open	—	X
I	Spherical and Dispersion Valves No. 2	Close/Open	—	X

* Cond/Gen/Pump—ON/OFF—for Units 2, 4, and 6 (CI).
† Transfer Breaker—ON/OFF—for Units 2, 4, and 6(CI).
‡ Indication ONLY—Units 2, 3, 5, and 6.
§ Indication on Units 2 and 6—CI on Unit 4.

C = CONTROL
I = INDICATION
CI = CONTROL and INDICATION

Table 10. Supervisory Capability—Thermalito Powerplant

TYPE	IDENTIFICATION	COMMAND AND STATUS	UNIT-IZED	NON-UNIT-IZED
CI	Master Control	Start/Stop/Check—Start Sequence—Stop Sequence	X	—
CI	Condenser Programming*	ON/OFF—Gen/Cond	X	—
C	Load Limit (Wicket Gate Limit)	Raise/Lower/Check	X	—
C	Speed Level	Raise/Lower/Check	X	—
CI	Bypass Dashpot	Close/Open	X	—
I	Load Control	Local/Manual—Auto Control	X	—
C	Field Rheostat	Raise/Lower/Check	X	—
C	Voltage Adjuster	Raise/Lower/Check	X	—
CI	Emergency Shutdown	Trip	X	—
I	Unit Tripped to Speed No Load	Tripped to Speed No Load	X	—
I	Incomplete Sequence	Start/Stop	X	—
I	Transfer to Local Control	Transfer to Local Control	X	—
I	13.8 kV Breaker (Gen)	Close/Trip	X	—
CI	Kaplan CAM Selector	Raise/Lower—Analog Position	X	—
I	Governor Transfer Valve Position	Main/Aux	X	—
I	Transfer Fault	Fault	X	—
CI	230 kV Load Interrupter Switch	Close/Open	X	—
I	Creep Detector	Creep	X	—
I	13.8 kV Pumping Breaker†	Close/Trip	X	—
I	Mode Orientacion	Blocking Gen—Pwr Complex Gen	—	X
I	Mode Orientation	Blocking Pump—Pwr Complex Pump	—	X
I	Master Station Transfer Control	Control Transfer	—	X
I	Master Check	Master Remote—Hydraulic Tel/Alarm—Command Error	—	X
I	Power Plant Gate Lock	Gate Lock	—	X
I	Station Service Power Transfer	Pwr Transfer	—	X
CI	Western Canal	Send/Check—Auto/Manual	—	X
CI	Richvale Canal	Send/Check—Auto/Manual	—	X
CI	PG&E Lateral Outlet	Send/Check—Auto/Manual	—	X
CI	Sutter Butte Canal	Send/Check—Auto/Manual	—	X
CI	Feather River Outlet	Send/Check—Auto/Manual	—	X
I	Thermalito Tailrace Water Level	Check—Level	—	X
CI	Thermalito Bypass Gate	Check—Close/Open	—	X
I	Thermalito Forebay Water Level	Level	—	X
CI	230 kV Breaker DW1 (562)	Close/Trip	—	X
CI	230 kV Breaker BW2 (662)	Close/Trip	—	X

* Cond/Gen/Pump—ON/OFF—for Units 2, 3, and 4.
† Indication ONLY Units 2, 3, and 4.

C = CONTROL
I = INDICATION
CI = CONTROL and INDICATION

Table 11. Supervisory Capability—Oroville Switchyard

TYPE	IDENTIFICATION	COMMAND AND STATUS	UNIT-IZED	NON-UNIT-IZED
I	Total Megawatts and Megavars for Oroville and Thermalito Display MW and MVARS for each plant	Analog Meters	—	X
I	Oroville Dam—Seepage Measurement Weir	Check—Level	—	X
I	Fish Barrier Water Level	Level	—	X
I	Tailrace Water Level Oroville	Level/Hi/Check—Water/Alarm	—	X
CI	Oroville Flood Control Outlet	Remote/Manual/Send—Check/Gate Position	—	X
CI	Thermalito Diversion Dam Spillway	Remote/Manual/Send—Check/Gate Position	—	X
CI	Thermalito Power Canal	Remote/Manual/Send—Check/Gate Position	—	X
CI	Palermo Outlet	Local/Remote—Levels/Send/Check	—	X
I	Master Check	Master/Remote—Hydraulic/TLM/Alarm—Command Error	—	X
I	Trashracks No. 1 and No. 2	Trouble	—	X

I = INDICATION
CI = CONTROL and INDICATION

Telemetering Subsystems. Three independent telemetering subsystems are provided for transmitting data and command signals over the communication channels between various facilities. These subsystems also convert the signals into suitable form for interfacing with transmitting and receiving equipment.

Each subsystem is capable of transmitting and receiving both analog and digital signals. The analog telemetering is of the variable-frequency type, with the frequency rate change not exceeding 35 hertz. The digital telemetering is a three-tone, frequency-shift-keying type, with a channel band width of 170 hertz.

Each subsystem includes tone receivers and transmitters, power supplies, tone generators, scanning and multiplexing devices, converters, line drivers, termination, and protection. Each subsystem also has components necessary for interfacing with equipment of the supervisory, automatic load-control, data logging, and alarm events and status change sequence subsystems.

The first telemetering subsystem is used in conjunction with the supervisory subsystem for digital transmission of commands, alarms, status changes, and requests for information between associated master and remote stations.

The second telemetering subsystem is used in conjunction with the data logging subsystem and recorders mounted on the graphic board located in the ACC. This subsystem continuously scans the metering instruments at both powerplants, Oroville Switchyard, Oroville intake structure, and Oroville flood control outlet.

The third telemetering subsystem is used in conjunction with the alarm events and status change sequence subsystem and the automatic load-control subsystem. This continuously scans three remote memories and assigned recorders.

Data Logging Subsystem. The purpose of the data logging subsystem is to record operational data acquired from specified facilities of the Oroville-Thermalito power complex. Data acquired by the data logging subsystem are collected, processed, and fed to a teletypewriter and strip-chart recorders.

The data logging subsystem receives digital data from Edward Hyatt Powerplant, Thermalito Powerplant, Oroville Dam flood control outlet, and Edward Hyatt Powerplant intake structure. The subsystem receives analog signals from Oroville Switchyard.

Digital data are transmitted to the master station in the Oroville ACC via a three-tone FSK telemetry link at a bit rate of 35 bits per second. Data from Edward Hyatt Powerplant contain unit megawatts, unit megavars, unit water flow (in and out), and water level in Lake Oroville.

Unitized data from Thermalito Powerplant contain megawatts, megavars, megawatt-hours (in and out), water flow (in and out), wicket-gate position, Kaplan cam identification (Unit 1 only), highest bearing temperature, and highest stator temperature. Data are also monitored on total power plant megawatts, total megavars, kilovolts, frequency, total water flow (in and out), and water levels in the Thermalito tailrace and Thermalito Forebay.

Data from the Oroville Dam flood control outlet contain information on the position of eight gates. Data from the Edward Hyatt Powerplant intake structure contain temperature information from 24 thermocouple devices. Data from Edward Hyatt Powerplant tailrace and Oroville Dam seepage weir contain information on the water levels at these sites.

Analog data from Oroville Switchyard contain information on megawatts and megavars from each of three 230-kV transmission lines, total megawatts and megavars, system voltage and frequency, temperature from 12 points including each of the six 230-kV cables, and two alarms (one for excessive cable temperature and one for cable system air temperature).

Data received are processed by a small computer (an 8K word, Varian Model 620I) and are fed to the logging teletypewriter and back-up, strip-chart recorders.

Alarm Events and Status Change Sequence Subsystem. The purpose of the alarm events and status change sequence subsystem is to record, in time ordered sequence, system operations during fault conditions. This subsystem and the data logging subsystem use the same computer, located in the master station in the Oroville ACC.

The alarm events and status change sequence subsystem records selected alarms and status changes from Edward Hyatt Powerplant, Thermalito Powerplant, and Oroville Switchyard. Alarms and changes in status for unitized and nonunitized contacts are sensed, combined with time of change, and transmitted to the data logging equipment in the Oroville ACC for printout. Alarms and events monitored are shown in Tables 12, 13, and 14.

The master station for the subsystem, located in the Oroville ACC, controls and time-synchronizes each of the three remote scanning stations.

Automatic Load-Control Subsystem. The automatic load-control subsystem is composed of two separate parts: (1) a load-control console located in the Oroville ACC, and (2) ten unit controllers located in the emergency control room in Edward Hyatt Powerplant and in the duplex switchboard at Thermalito Powerplant. Power generated by the Oroville-Thermalito complex can be controlled by the automatic dispatch system (ADS) of Pacific Gas and Electric Company located in San Francisco. The ADS originates a load signal which is transmitted to the Oroville-Thermalito load-control subsystem using microwave and powerline carrier equipment. This signal is received by the load-control console. It is the

Table 12. Alarms and Events Monitored—Edward Hyatt Powerplant

UNITIZED POINTS, TYPICAL EACH UNIT

Gov. Tank Low Oil Level
Gov. Low Oil Pressure
Gov. Sump Tank Low Oil Level
Gov. Standby Oil Pump Started
Turbine DC Oil Pump Operating
Turbine Guide Bearing High Metal Temp
Turbine Guide Bearing Temp Relay
Turbine Guide Brg. Cooling Water Low Flow
Turbine Guide Brg. Discharge Oil Temp
Turbine Guide Brg. High Oil Level
Turbine Guide Brg. Low Oil Level
Turbine Packing Box Temp
Gen. Upper Guide Brg. Metal High Temp
Gen. Lower Guide Brg. Metal High Temp
Gen. Lower Guide Brg. Water Low Pressure
Gen. Lower Guide Brg. Oil High Temp
Gen. Lower Guide Brg. Water Low Flow
Gen. Thrust Brg. Metal High Temp
Gen. Thrust Brg. High Temp
Unit Brg. High Temp
Gen. Thrust Brg. Water Low Pressure
Gen. Thrust Brg. Low Oil Pressure
Gen. Thrust Brg. High or Low Oil Level
Gen. Thrust Brg. Oil High Temp
Gen. Thrust Brg. Water Low Flow
TSV Comp. Cooling Water Low Flow
Runner Seal Ring Cooling Water Low Flow
TSV Comp. Extreme High Pressure
TSV Press. Tank Low Oil Level
TSV Water Filter Differential
TSV Sump Low Oil
TSV Low Air Pressure
TSV Tap Guard Valve Air Revr. Low Press
TSV Tap Guard Valve Close
Main Transformer Sudden Pressure
Gov. Air Pressure Failure
Unit Cooling Water Strainer‡
230 kV Cable Pilot Wire Monitoring Relay

Volts Per Cycle (T)
Main Transformer Winding Temp RTD
Main Transformer Winding Temp
Main Transformer Oil High Temp
Transformer Differential & CO_2 Release
Main Transformer Differential
Main Transformer Low Oil Flow
Main Transformer Cooling Water Low Flow
Main Transformer Low Oil Level
Main Transformer Press Relief Device
Main Transformer Tank Low Press
Main Transformer Cylinder Low Gas Press Relay
Gen. Brake Air Low Pressure
Unit Cooling Water Relief Valve
Unit Bearing Cooling Water Strainer
Air Cooler Header Water Low Pressure
Gen. Air Cooler Water Low Flow
Gen. Air Cooler High Temp
Gen. Differential
Gen. Differential & CO_2 Release
Gen. Stator Ground
Gen. Field Ground
Reduced Freq. Gen. Stator Ground*
Gen. Loss of Field
Gen. Overload
Under Frequency
Reverse Phase Sequence†
Incomplete Starting Sequence
Stator Winding RTD High Temp
Gen. Field RTD High Temp
Neg. Sequence
Loss of Instrument Potential
Synchronizing DC Failure
Automatic Synchronizing DC Failure
Starting Sequence DC Failure
Protective Relaying DC Failure
Overvoltage Frequency Compensated

Voltage Restrained Overcurrent
Shaft Deflection
Unit Creeping
Unit Overspeed
Unit Partial Shutdown
Unit Shutdown and Lockout
Unit Cooling Water Transfer
Grease Pump Failure
Wicket Gate Shear Pin Failure
Gen. Over Excitation
Regulator Overload
Exciter DC Failure
Interlocking DC Failure†
Runner Band Drain Valve Failed to Close
Runner Band Drain Valve Failed to Open
Transfer to Manual Control
Auto Starting (Master Start)
Auto Start Sequence Complete
Auto Stopping
Generator Operation
Reduced Freq. Operation*
Synchronous Condenser Operation
Motor Operation†
Reduced Freq. Partial Trip Relay
Local Manual Load Control On
Remote—Auto Load Control On
Voltage Regulator On
Voltage Regulator Trip
Wicket Gate Open
Exciter Field Breaker Open
Exciter Field Breaker Close
Reverse Exciter Breaker Open†
Reverse Exciter Breaker Close†
Turbine Water Depressed
Penstock Valve Open
Penstock Valve Close
480V Control Center Power Transfer (2)

NONUNITIZED POINTS

PSB Distr. Center Power Transfer
Loss of AC from 480V Control Center
DC System Failure
Station Service Brkr. Trip
Station Service Transformer Diff. (4)
Station Service Transformer High Temp (4)
Switchgear Ground
Main Transformers Emerg. Cooling Water (2)
Transformer Emerg. Cooling Water Low Flow (2)
Transformer Cooling Water Relief Valve (2)
Gov. Air Revr. Low Air Press
Instrument Air Low Press
Control and Brake Air Header Low Press

Sewage System Failure
Brake and Control Air Comp. Cooling Water Low Press
Depressing and Service Air System Low Press
Depressing & Service Air Comp. Disch. Air Temp (2)
Gov. Air Comp. Cooling Water Low Press (2)
Standby Cooling Water Main Valve Activated (2)
Service Air Comp. Cooling Water Low Press (2)
Chiller Cond. Cooling Water Strainer Diff. Press
Dewatering Sump High Level
Drainage Sump High Level

Dewatering Gallery Sump High Level
Powerhouse Oil Room CO_2 Release
Smoke Detection Equipment Failure
Return Air High Temp
Smoke Detected
230 kV Cable Air Temp
River Outlet Valve Gallery Flooded
River Outlet Valve Low Oil Press
Outlet Portal Trashrack Wrong Position (2)
Circuit Breaker Trip (4)
Circuit Breaker Close (4)
480V Power Transfer (4)
Light. Distr. Ctr. Power Transfer (2)
Pumps Tripped by PG&E

* Units 1, 3, and 5 only
† Units 2, 4, and 6 only
‡ Units 2 and 4 only

Table 13. Alarms and Events Monitored—Thermalito Powerplant

UNITIZED POINTS, TYPICAL EACH UNIT

Thrust Bearing High Oil Level
Thrust Bearing Oil Temp
Thrust Bearing Low Oil Press
Thrust Bearing Low Oil Level
Thrust Bearing High Temp. Relay
Kaplan Unit Oil Head Lower Reservoir Low Level*
Kaplan Unit Oil Head Excess Leakage*
Kaplan Unit Oil Head Upper Reservoir Low Level*
Kaplan Unit Oil Head Upper Packing Box Temp*
Kaplan Unit Oil Head Lower Packing Box Temp*
AC Bearing Oil Pump Low Oil Flow
Stator Winding High Temp
Gen. Guide Bearing Temp Relay
Gen. Bearing Cooling Water Low Flow
Gen. Air Cooler Header Water Low Flow
Unit Cooling Water Low Flow
Upper Runner Seal Water Low Flow
Lower Runner Seal Water Low Flow†
Gov. Sump Tank Low Oil Level
Gov. Low Oil Press
Turbine Packing Box High Temp
Turbine Guide Bearing High Oil Level
Turbine Bearing Disch. Oil Temp
Turbine Guide Brg. Cooling Water Low Flow
Turbine Bearing Oil Supply Low Flow
Turbine Guide Bearing Temp Relay
Unit Bearing High Temp
Turbine Guide Bearing Low Oil Level
DC Guide Brg. Oil Pump Start Initiated
Main Transformer Sudden Pressure
Main Transformer Winding Temp Relay
Main Transformer Winding Temp
Main Transformer Low Oil Level
Main Transformer Oil Temp
Main Transformer Tank Press
Main Transformer Hot
Main Transformer Inert Air
Main Transformer Water Spray
Main Transformer Diff. Auxiliary Relay
Main Transformer Fan Supply or Control Voltage Low
Overcurrent Voltage Restrained
Overvoltage Frequency Compensated
Reverse Phase Sequence†
Gen. Loss of Field
Gen. Field Ground
Gen. CO_2 Release
Neg. Sequence Phase Unbalance
Incomplete Starting Sequence
Directional Overcurrent Relay
Under Frequency Relay†
Unit Partial Shutdown
Unit Shutdown and Lockout
Emergency Shutdown Solenoid
Gen. Brake Air Press Low
Gen. Air Cooler Disch. Air Temp
Grease Pump Failure
Shaft Deflection
Unit Creeping
Unit Overspeed
Gen. Diff. Auxiliary Relay
Runner Band Drain Valve Failed to Open†
Runner Band Drain Valve Failed to Close†
Gov. Pressure Tank Low Oil Level
Automatic Starting
Automatic Stopping
Transfer to Manual Control
Generator Operation
Motor Operation†
Synchronous Condenser Operation
Motor Auto Start Sequence Complete†
Voltage Regulator Switch Position Manual
Voltage Regulator Switch Position Auto
Exciter Field Breaker Closed
Turbine Water Depressed
Wicket Gate Open
13.8kV Gen. Circuit Breaker Trip (4)
13.8kV Gen. Circuit Breaker Close (4)
13.8kV Motor Circuit Breaker Trip† (3)
Auto Load Control On
Kaplan Sump High Water*

NONUNITIZED POINTS

Drainage & Dewatering Pumps Controller Low Air Press
Control Air Low Pressure (4)
Powerplant Oil Room CO_2 Release
DC Bus Ground or Low Voltage
Loss of Essential AC
Depressing & Service Air System Low Press
Depressing & Service Air Compr. Disch. Air Temp (3)
Dewatering Sump High Water Level
Drainage Sump High Water Level (2)
Draft Tube Dewatering Valve Pit Sump High Water (2)
High Press Air Compr. Cooling Water Press (2)
Service Air Compr. Cooling Water Press (3)
Smoke Detected
Smoke Detector Equipment Failure
Control Room High Air Temp
Generator Floor High Air Temp
480V Tie-Breaker Transfer (2)
Circuit Breaker Trip (6)
Circuit Breaker Close (6)
PCB Open (2)
PCB Close (2)
PCB Trip (2)
PCB Lp Sys Lo PSI
PCB Hp Sys Lo PSI
Pumps Tripped by PG&E
PG&E Load Shed Sig Loss
230kV Int Sw Trip (4)
Xtrm Air Comp Run (2)
PCB Hp Sys Lo PSI
SF_6 Diff Press (2)
PCB Lp Sys Lo PSI
PG&E Standby Lo Volts

* Unit 2 only
† Units 2, 3, and 4 only

Table 14. Alarms and Events Monitored—Oroville Switchyard

UNITIZED POINTS, TYPICAL EACH UNIT		
Ckt. Brkr. Low Press System Low Press	Ckt. Brkr. Trip	Unit Disconnect Switch Open*
Ckt. Brkr. High Press System Low Press	Ckt. Brkr. Close	Unit Disconnect Switch Close*
Ckt. Brkr. Fault Trip	230 kV Cable Pilot Wire	
NONUNITIZED POINTS		
Ckt. Brkr. Trip (3)	Sta. Serv. Transformer Winding Temp	Main Bus Sect. Switch Close
Ckt. Brkr. Close	230 kV Cable System Trouble	Bus Section Lockout Relay (3)
Transformers High Temp	Intake Gate Trouble (2)	Main Bus Undervoltage (3)
Sta. Serv. Transformer Oil Temp	Control Bldg. Oil Storage Room CO_2 Release	Communication Channel Reach Failure (3)
Sta. Serv. Transformer Differential	Control Bldg. Sump Pump	Ckt. Brkr. Close (3)
Sta. Serv. Transformer Sudden Press	Switchyard DC Circuit Failure (3)	Line Disconnect Switch Open (3)
Sta. Serv. Transformer Winding High Temp	230 kV Bus Protective Relaying DC Failure	230 kV Cable Gallery High Air Temp
Sta. Serv. Transformer Main Tank Oil Level	DC System Power Failure	Trashrack Raised on Pumping
Sta. Serv. Transformer LTC Tank Oil Level	Core Block Drainage Pump Running (3)	Sewage System Failure
Sta. Serv. Transformer Main Tank Press Relief	Ckt. Brkr. High Press System Low Press (3)	Fallout Condition
Sta. Serv. Transformer LTC Tank Press Relief	Ckt. Brkr. Low Press System Low Press (3)	Pumping Mode of Operation
Sta. Serv. Transformer Cylinder Low Press	Display Panel Trouble	Generating Mode of Operation
Sta. Serv. Transformer Tank Low Press	Ckt. Brkr. Fault Trip (3)	Power Canal Level High
Sta. Serv. Transformer Tank High Press	Ckt. Brkr. Trip (3)	Power Canal Level Low
	Line Disconnect Switch Close (3)	Load Control Suspended
	Main Bus Sect. Switch Open (2)	

* Units 1, 3, and 5 only

responsibility of the ACC operator to ensure that sufficient generating capacity is available to the load-control subsystem to cover scheduled ADS generation. This is accomplished by starting units, bringing them to speed-no-load, and switching them into the load-control subsystem either manually or through the supervisory system.

The load-control subsystem can also be operated manually through the load-control console in the absence of the ADS signal. This is accomplished by entering block generation amounts through the schedule setter on the load-control console. Figure 28 shows the automatic load-control console.

In the generating mode of operation, the load-control console matches required water flow at Edward Hyatt and Thermalito Powerplants. The console also distributes load on operating units in both Powerplants in the most efficient manner for the desired generating load. The unit controllers compare signals representing actual and computed unit generating requirements. The output signal from each unit controller is fed to the governor speed adjust until both actual and computer signals to the unit controller are equal.

In the pumping mode of operation, the load-control console adjusts the position of wicket gates of the three pumping units at Hyatt to achieve maximum efficiency at actual pumping head. Pumps at both Powerplants are started manually or tripped automatically as required by excessive changes in the water level of the Thermalito Power Canal. Unit controllers compare the signals representing the actual and computed positions of the wicket gates. The output signal is then cut off and no further control takes place until the pumping head at Oroville changes.

Devil Canyon Control System

The purpose of the Devil Canyon Powerplant control system is to provide local automatic and remote control of the plant from the Southern California ACC or from the POCC.

Local Automatic Control. The local automatic control system is provided to (1) regulate the turbine power output; (2) maintain the Devil Canyon Afterbay level within designated limits; and (3) match, insofar as possible, turbine flow to afterbay outflow. Major components of the control system are the afterbay water-level sensor, a control switchboard with associated metering, and the governor speed-adjust transducer.

The control switchboard, located in the plant control room, contains setpoint devices and meters and indicating meters for total afterbay flow, total plant flow, unit flow, and afterbay water level. Recorders are provided for afterbay water level, total water flow, and unit flow.

The local automatic control system was designed to coordinate operation of the turbines and Afterbay under the following conditions (operating modes):

1. Turbine flow matches total afterbay outflow, with corresponding varying power output.

2. Turbine flow matches total afterbay outflow within minimum and maximum flow limits (variable power output within minimum and maximum limits).

3. Constant turbine flow independent of total afterbay outflow (constant power output).

The control system adjusts impulse turbine needles by providing a variable, direct-current, command signal to the governor speed-adjust transducer. A 0-volt signal corresponds to the speed-no-load (SNL) needle position, and a 1-volt signal represents the fully open (or 100%) needle position. The needles are linearly positioned from the SNL position to 100% open for voltages between 0- and 1-volt DC. The speed-adjust transducer adjusts the needles by direct modulation of the governor pilot valve cage. This modulation is provided, in addition to the normal pilot valve cage movement caused by fly-ball action, in response to load variations in the utility system.

The control system is regulated through adjustment of four setpoints, either locally from the control switchboard or remotely. These setpoints are:

1. Afterbay water level, in feet
2. Minimum needle position, in percent
3. Maximum needle position, in percent
4. Controller gain, in percent of needle stroke per ½-foot change in afterbay level.

The control system is capable of matching the steady-state turbine flow to total afterbay outflow provided total afterbay outflow remains within the range between the minimum needle position and maximum needle position setpoints.

When afterbay water level is above afterbay water-level setpoint, turbine needles will be at the position selected as minimum needle position setpoint. As afterbay water level drops below setpoint level, the control system will cause the turbine needles to open farther at a rate determined by the controller gain setpoint. If sustained afterbay outflow is in excess of turbine flow selected as the maximum needle position setpoint, the Afterbay will drain unless setting of the maximum needle position setpoint is increased or outflow is reduced. If sustained afterbay outflow is less than turbine flow selected as the minimum needle position setpoint, the Afterbay will be overtopped and excess flows will be discharged through the spillway.

The minimum needle position setpoint ensures that power output of the plant does not drop below a scheduled amount.

Remote Control. A small computer system (an 8K, Honeywell H-316) is used at the plant to provide the interface with the aqueduct control system for remote control. This computer is interfaced to the local automatic control system and to a standard communications system at the plant. An operator at the ACC has command, data, status, and alarm capabilities to the plant as shown in Table 15.

Operation of the Devil Canyon Afterbay complex is closely tied to operation of the plant. Direct-wire operation of the flow gates controlling outflow from the Afterbay is possible from the Devil Canyon Powerplant. In addition, complete remote monitoring and control of the Afterbay is possible through a separate small computer system installed in the afterbay control house. An operator at the ACC has control and data monitoring capability of the Afterbay as shown in Table 16.

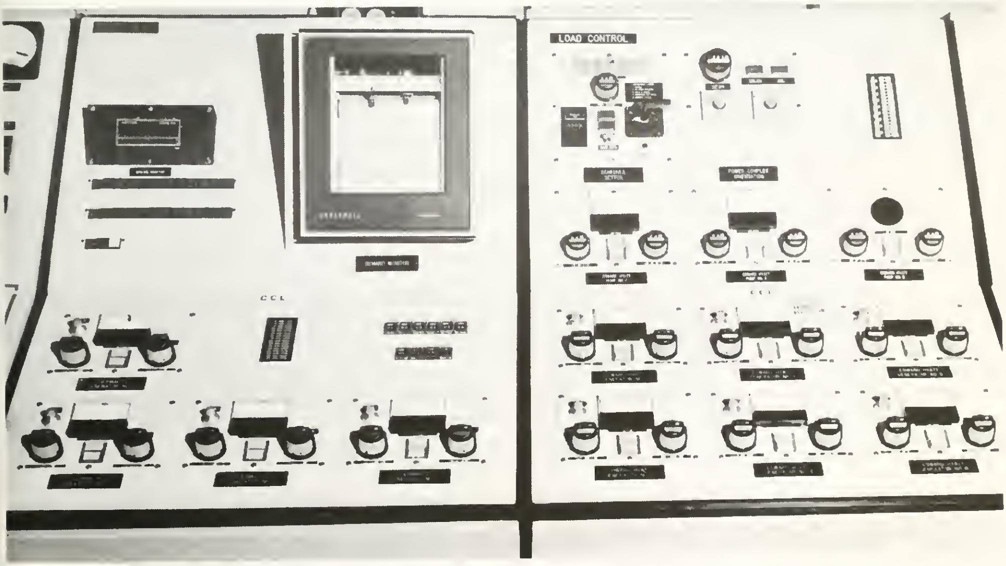


Figure 28. Automatic Load Control Console

Table 15. Information Exchanged Between the Devil Canyon Powerplant System and the ACC

COMMANDS

Telephone Audio Signal
Unit Start (each unit)
Unit Stop Normal (each unit)
Unit Stop Emergency (each unit)
Unit Gain Setpoint (each unit)
Afterbay Water Level Setpoint
Unit Needle Position Max. Setpoint (each unit)
Unit Needle Position Min. Setpoint (each unit)
Select 2, 4, or 6 Nozzles (each unit)
Emergency Close No. 1 and No. 2 Headworks Valves

DATA

Afterbay Water Level
Plant Flow Rate (CFS)
Main Bus Voltage
Real Power
Vars (each unit)
Afterbay Water Level Setpoint
Unit Needle Position Max. Setpoint (each unit)
Unit Needle Position Min. Setpoint (each unit)
Unit Gain Setpoint (each unit)
Plant Energy (kWh)

STATUS

Plant
- Headworks Valve No. 1 Closed
- Headworks Valve No. 2 Closed
- Unit ON
- Unit ON
- Unit ON

Unit (each unit)
- Unit under Local Control
- Unit under Area Control Center Control
- Unit I/P (in parallel)
- Unit S/D (shutdown)
- Unit O/S (out-of-service)
- Turbine Shutoff Valve Closed
- 6 Nozzles in use
- 4 Nozzles in use
- 2 Nozzles in use

ALARMS

Plant
- Building Entry
- Plant Warning
- Telco Equipment Failure
- Transmission Line Breaker Tripped
- Plant Local Control
- Primary Power Failure
- Drainage Sump High
- Main Bus Undervoltage
- Transformer Trouble
- Main Breaker Lockout
- Hydraulic System Trouble
- Water Level Controller Failure
- Warning Headworks Valves—Gates Closing
- Headworks Primary Power Failure
- Headworks Valves—Gates Emergency Closure Activated
- Headworks Trouble

Unit (each unit)
- Unit Lockout
- Valve Trouble
- Turbine Bearing Temperature High
- Start Failure
- Electrical Fault
- Unit Creep
- Generator Stator Temperature High
- Vibration High (Shaft Deflection)
- Overspeed
- Generator Bearing Temperature High

Table 16. Information Exchanged Between the Devil Canyon Afterbay System and the ACC

COMMANDS

Manual Control, Automatic Control } for Santa Ana Valley Pipeline
Telephone Audio Signal
Flow Rate Setpoint for Santa Ana Valley Pipeline
Gate Position Reference (each turnout—4 total)

DATA

Flow Rate Setpoint for Santa Ana Valley Pipeline
Flow Rate in Santa Ana Valley Pipeline
Gate Position Reference (each turnout)
Gate Position (each turnout)

STATUS

Manual Control, Automatic Control } for Santa Ana Valley Pipeline
Gate Closed (each turnout)

ALARMS

Loss of Signal CI Line
Loss of Signal DSA Line
Telco Equipment Failure
Building Entry
Remote Control Lockout
Computer Memory Parity Error
Computer Failure
Computer High Temperature
Gate Failure (each turnout)
Gate Lockout (each turnout)

Design of Aqueduct Area Control Centers

The concept of five area control centers, their locations, and the area of the Project that each controls is described in Chapter IV, "Operations Control Plan." The Oroville Area Control Center is an integral part of the design of the Oroville-Thermalito control system. The remaining four aqueduct area control centers are functionally similar and are described herein.

Functional Description

Each ACC is the master control station of an area of the State Water Project. It shares this status with the POCC in Sacramento which can assume the function of an ACC (except the Oroville ACC) in a back-up mode whenever jurisdiction is assumed by the POCC. The four Aqueduct ACCs and the POCC have compatible communications and are integrated into one overall control system.

The major components of an ACC are as follows:
1. Computer System
2. Communications Equipment
3. Operator's Control Console

Figure 29 is a block diagram of a typical ACC.

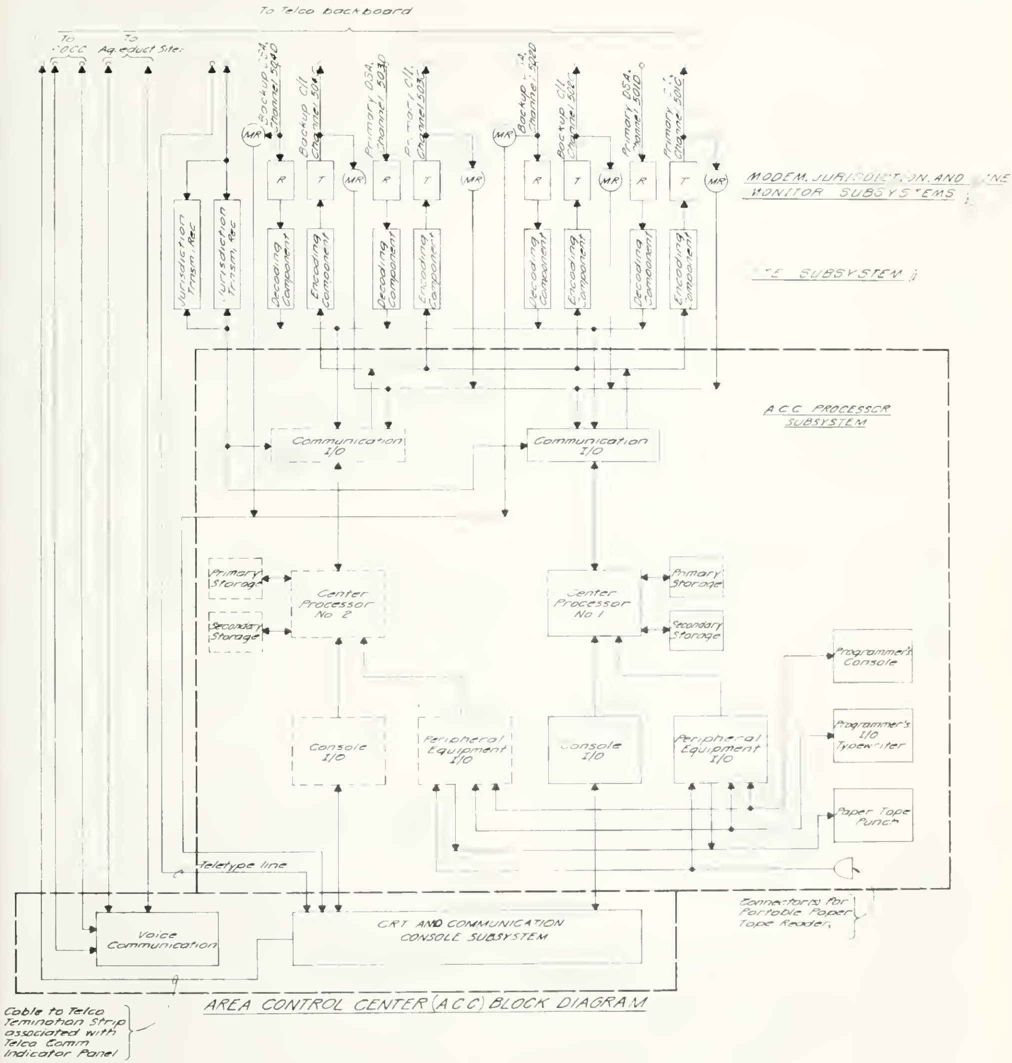


Figure 29. Functional Block Diagram—Typical Area Control Center

Computer System

The computer systems vary in size from 24K to 32K words of 16-bit core memory. All have secondary storage in the form of a magnetic disk or drum. The amount of secondary storage varies from 262K to 512K words (16 bit). The computers are of the type designated as general-purpose mini-computers as manufactured during the years 1968–1972.

The computers utilized in the Delta, San Luis, and San Joaquin ACCs are Hewlett-Packard Model 2116B. The computer utilized in the Southern ACC is a Honeywell Model 316.

Standard peripheral equipment is provided including a paper tape reader and punch and a teletype input/output device. This peripheral equipment is used for programming purposes only. Nonstandard peripheral equipment includes special-purpose equipment required to interface to the communications equipment, the operator's control console, and the jurisdiction control system. The computer system and all other control system equipment in the ACC are powered by an uninterruptible power supply.

The functions of the computer system can be categorized as data acquisition, information display, and command execution. Data acquisition is a continual automatic function. In a polled communication system, each piece of information transmitted from a remote site to the ACC is transmitted as a result of a specific request (interrogation) issued from the ACC. These interrogations are continually being transmitted from the ACC at a rate of about eight per second. The returning data are validated by the ACC computer and stored in memory for future use. The computer also performs certain arithmetic calculations on some of the data (e.g., flow rates through check structures, calculated from differential head and gate position) and stores the results for future use. Data are interrogated (scanned) at maximum intervals of approximately two minutes with some data (e.g., alarms, certain status information, and certain power parameters) being scanned every 15 seconds. Thus, the most current information is always available to the operator. The computer also formats these data for presentation to the operator through various devices of the operator's control console. For control, the computer accepts commands from the operator through the operator's control console for immediate or later execution.

If the POCC is in control of the area (as determined by the jurisdiction control system), the ACC

Figure 30. Typical Operator's Console—Area Control Center

Figure 31. Typical Communications Console—Area Control Center

computer still performs the data acquisition function by accepting and storing incoming data received in response to the POCC scanning and makes these data available to the operator. The ACC computer also inhibits interrogations and commands from being transmitted from the ACC during the periods of time the POCC is in control.

Communications Equipment

The communications equipment in the ACC is functionally similar to the standard communication systems at the remote sites. The modem transmitters at the ACC continuously transmit a signal to the communication line. During the period between outgoing interrogation messages, a 1,200 hertz "carrier" tone is applied to the line. The purpose of this signal is to keep any noise on the communication line from being interpreted by the remote site receivers as valid data signals.

The communication terminal equipment at the ACC is the simplest of all terminal equipment installations. It does not have the enhancements of the remote sites but merely performs "sync" recognition/generation and serial-to-parallel conversion of the received messages.

Each ACC is designed for the use of two communication systems, with each having capability for both an "A" and "B" communication line. The only ACC at which both communication systems are in use is the San Joaquin. At the other ACCs, the second system is provided for future expansion.

Operator's Control Console

The operator's control console is the interface device between the operator and the computer system. The console is a two-station, sit-down, control console containing the following principal functional components:

1. Cathode Ray Tube (CRT) display and control system
2. Alarm display panel
3. Console printout device

Figure 30 shows the layout of the operator's console.

Facing the operator's console is a communication console containing a mobile radio terminal and other voice communications equipment. Figure 31 shows this console.

CRT System. Monitoring and controlling of remote sites from the ACC are accomplished through the CRT system. This is the main operator input/output device to the computer. Figure 32 shows a typical CRT station layout.

To display information, the operator calls up CRT "pages" of information by use of the "page" keyboard matrix (Figure 33). Depressing these keys interrupts the computer, which in turn causes the requested page containing the latest data to be displayed to the operator over the appropriate CRT device.

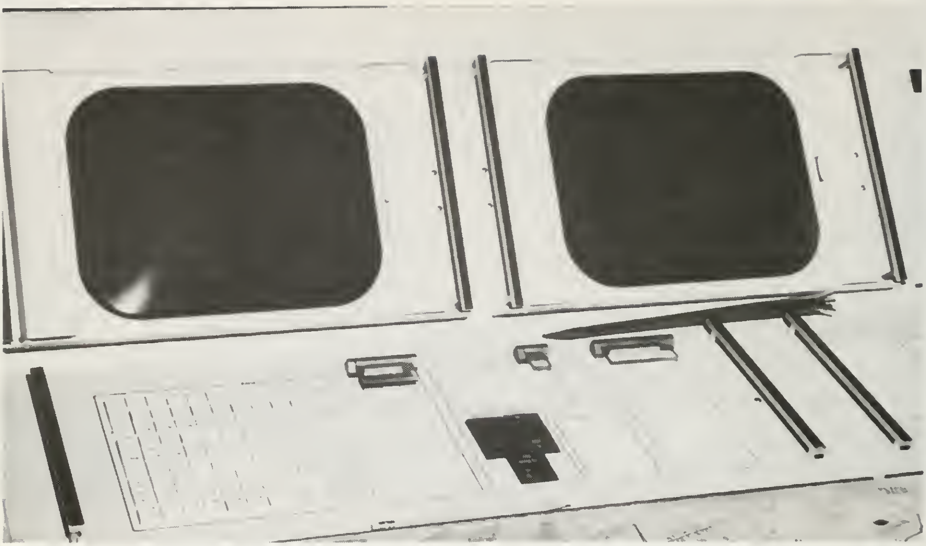


Figure 32. Typical CRT Station—Area Control Center Operator's Console

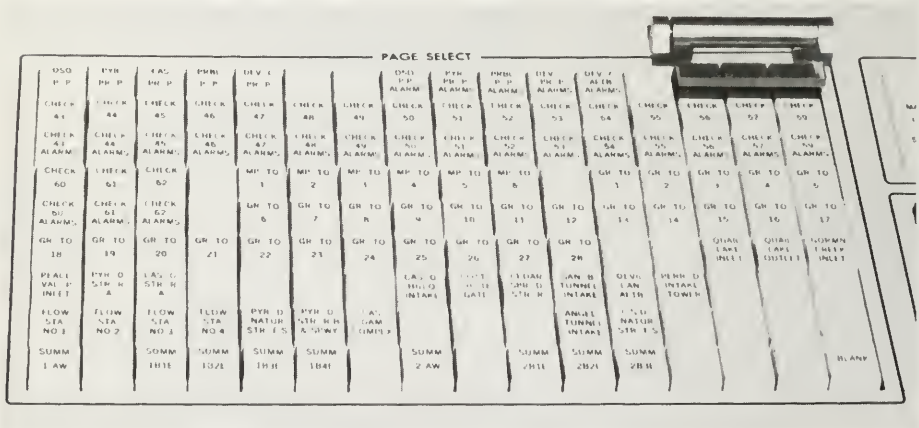


Figure 33. Typical Page Keyboard Matrix—Area Control Center Operator's Console

These pages are also used by the operator to execute commands to the system. If the operator calls the page in the "edit" mode, the page will be displayed with "underline" characters positioned in variable locations into which the operator can enter information. Figure 34 shows a check structure page displayed in the edit mode. By positioning a cursor using the cursor positioning controls, the operator can enter commands and/or numeric characters as appropriate in the NEXT COMM, REF, or TIME columns of the CRT page. When he has completed entering the information, the page can be executed, causing it to be transmitted to the computer. The computer validates the commands and stores them for transmission to remote sites as determined by the entry in the TIME column. Using this capability, the operator can "preprogram" many commands for automatic execution by the computer at the appropriate time of day. Figure 35 shows the editing capability available to the operator.

Pumping plants are controlled in a like manner. Figure 36 shows a typical pumping plant CRT page.

The operator can request display of "nonedit" summary pages. These display the same operating parameters at all sites within the control area but cannot be edited for command entries. Figure 37 is a typical summary page of information.

There is a complete set of page keys, cursor positioning keys, and command entry keys for each of the two operating stations.

Alarm Display Panel. A single-alarm display panel is common to both operating positions of the console. Figure 38 shows the alarm panel. This panel annunciates each alarm as it is received by the ACC computer by flashing the appropriate site window. The operator acknowledges the alarm and causes the specific alarm conditions to be displayed on the panel by use of the alarm panel detail keyboard matrix which is located between the two operating positions and common to both. Figure 39 shows this keyboard matrix.

In addition, alarms are displayed on the appropriate CRT page and are typed out over the console printer. Additional alarms are provided on the console concerning the jurisdiction system and computer peripheral equipment.

Console Printer. The operator's console is provided with a printer which automatically logs all alarms and changes in status. It also is used to log certain operating data on operator demand.

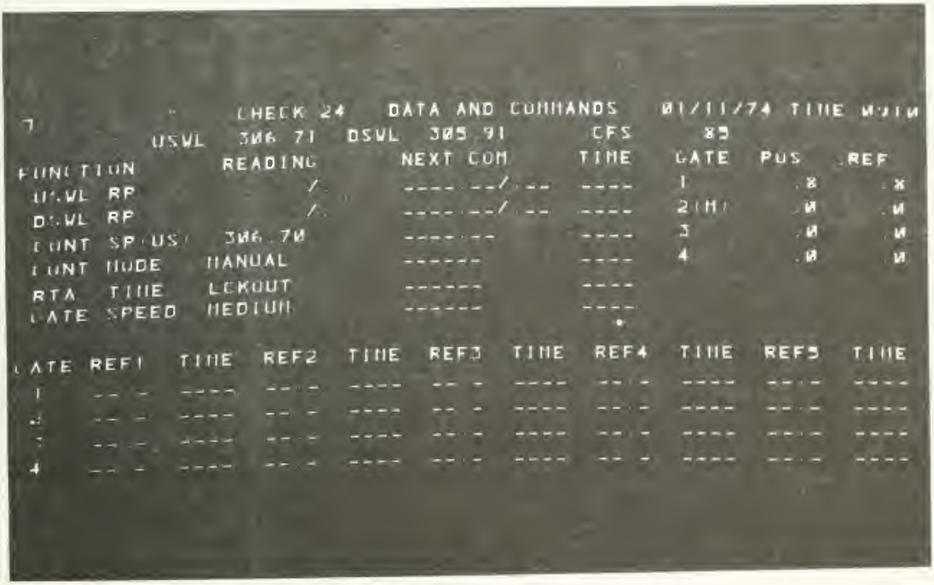


Figure 34. Check Structure CRT Page in "Edit" Mode

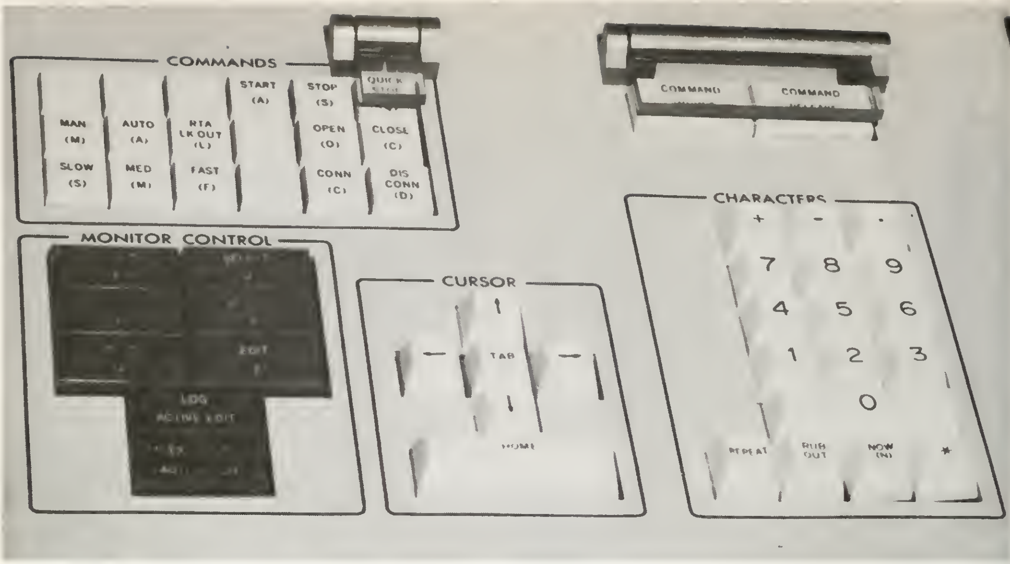


Figure 35. CRT Editing Capobility

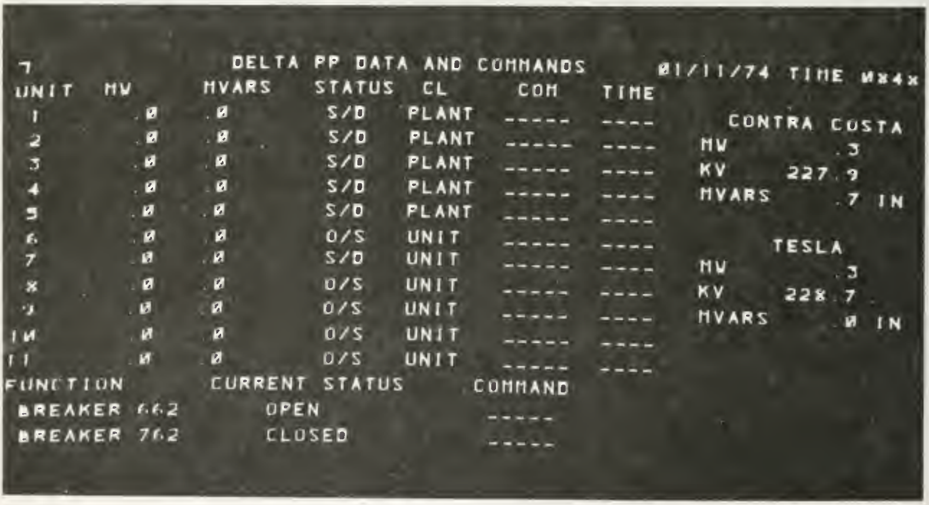


Figure 36. Pumping Plant CRT Page Shown in the "Edit" Mode

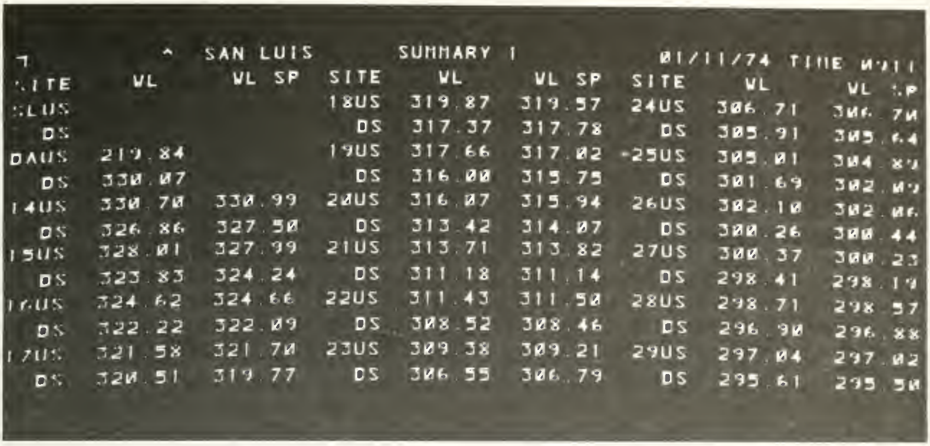


Figure 37. Summary CRT Page

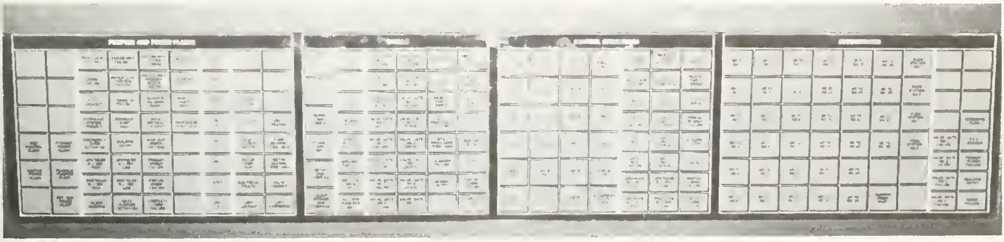


Figure 38. Typical Alarm Panel—Area Control Center Operator's Console

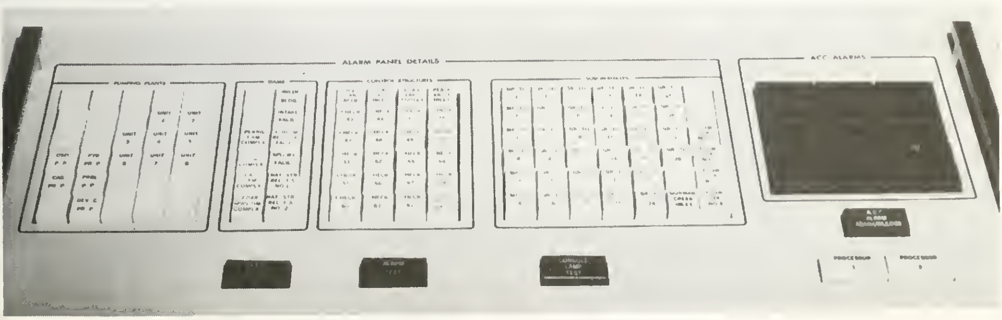


Figure 39. Alarm Panel Keyboard Matrix—Area Control Center Operator's Console

Jurisdiction Control

Normally, control of the Project is carried out from the ACCs. In the event an aqueduct ACC is unable to carry out this control, a back-up control capability is provided from the POCC. The function of the jurisdiction control system is to ensure that equipment in the ACC is completely disconnected from the communication line during the periods the POCC is in control. This system is described in detail in the section "Design of the POCC".

Emergency Power

Each ACC is provided with power from an uninterruptible power supply consisting of a static inverter with suitable battery supply. The batteries are continually charged with either primary commercial power or an emergency engine generator.

Design of the Project Operations Control Center

The Project Operations Control Center in Sacramento serves as the central point for coordination and direction of all water and power operation of the State Water Project. It provides a back-up control to the aqueduct area control centers when the ACCs are out of service for either preventive or corrective maintenance. Also, it provides for certain automatic, projectwide, computerized reactions to emergency conditions affecting project operations. Figure 40 shows the facilities of the POCC.

The POCC consists of the following major components:

1. Computer System
2. Wall Displays
3. Dispatcher's Console
4. Cathode Ray Tube (CRT) System
5. Printers
6. Communications

Figure 41 is a block diagram of the POCC equipment.

Figure 40. Project Operations Control Center

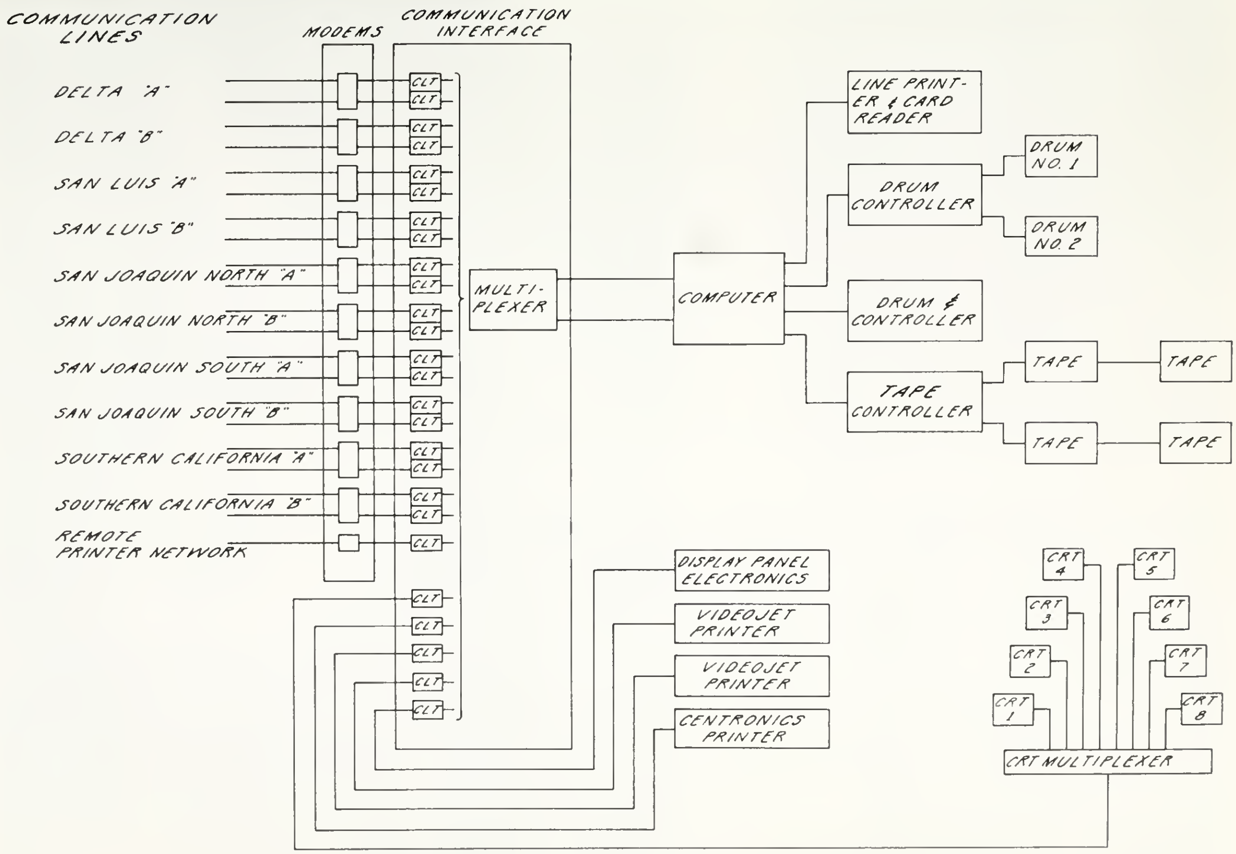


Figure 41. Functional Black Diagram—Project Operotians Control Center

Computer System

The computer system is the main element in the POCC. The computer is a UNIVAC 418-II, general-purpose, digital computer. It is the same computer used in the South Bay Model study (Chapter III) but expanded to meet the needs of the POCC.

System components are a central processor with 65K words (18 bit) of core memory; three drum memories, one of which is 65K words and two of which are 262K words each; a card reader-line printer; and four magnetic tape units with controller. Figure 42 shows this computer system.

The computer system is interfaced to the wall displays, CRT equipment, printers, and communications system. It has been programmed by department personnel to provide all necessary capability.

Wall Displays

A wall display panel provides continuously updated information on alarms and selected status and data for the Project. This panel is a floor-to-ceiling display built on a curve with a total length of approximately 52 feet. The left 16 feet of panel are constructed from standard perforated power dispatcher's board. It was supplied blank and has been labeled by the dispatchers to reflect the single-line diagrams of the various pumping and power plants in the Project and the power transmission lines and substations feeding them. Lamps, which are manually lighted, indicate the status of switchyard and transmission line breakers. Figure 43 shows this portion of the panel.

To the right of these panels, the display panel is constructed of plywood with a single-line profile of the Project silk-screened onto the face. Beginning on the left end of this portion of panel with the Oroville-Thermalito complex, the profile extends "down project" to Lake Perris on the right end of the panel.

Each major feature of the Project is appropriately designated with a special symbol and is equipped with an alarm indicator. In some cases, special rear-projection digital readouts display data and status information. Figure 44 shows the finished layout of the wall display panel.

The wall display is updated by the POCC computer using a serial, 4,800-bit-per-second, output line. The computer formats a special message containing a device identification (alarm indicator or digital readout) and other pertinent data. This message is received by the wall display electronics where it is decoded and routed to the proper location on the panel.

Dispatcher's Console

There are four operating positions for the dispatchers in the POCC. The two shift dispatchers operate from a modified, double-horseshoe console which provides surface space for the CRT equipment, typewriters, calculators, voice communications equipment, and writing areas. Storage space within the console also is provided for reference and operating documents.

Figure 42. Project Operations Control Center Computer System

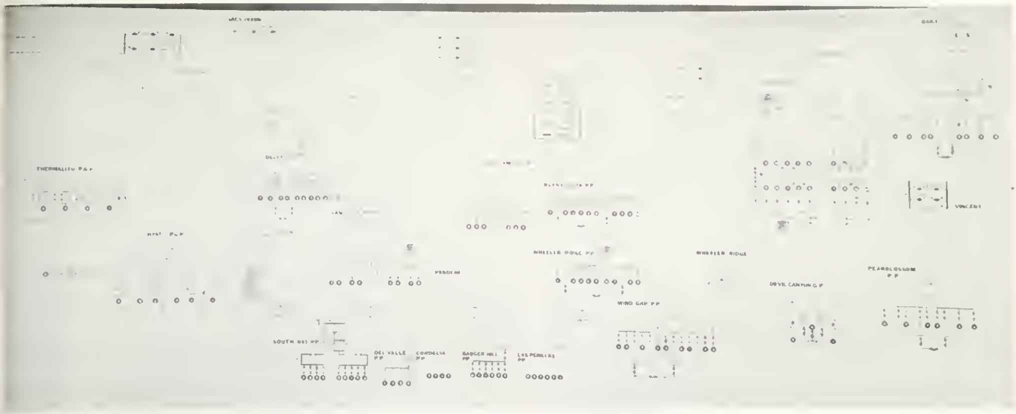


Figure 43. Electrical Single Line Display Panel—Project Operations Control Center

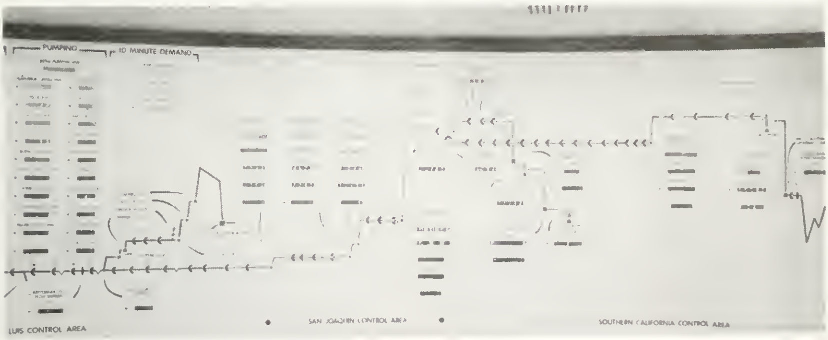


Figure 44. Graphic Display—Project Operations Control Center

CRT System

The CRT system consists of eight terminals coupled to the computer through a CRT Multiplexer via a 9,600-bit-per-second input/output (I/O) line. The CRTs are the main dispatcher I/O device to the computer for monitoring and control.

Each of the two shift dispatchers' positions have two CRT terminals with a single switchable keyboard. A fifth CRT device, an alarm and events display without keyboard, is centrally located between the operating positions and is used to display the most recent 16 alarms or status changes of the facilities. The sixth CRT terminal is located on the programmed outage dispatcher's console, the seventh CRT is located on the scheduling dispatcher's console, and the eighth is located in the computer room. All CRT terminals (except for the alarm CRT) have full monitoring and control capability and can be completely interchanged as necessary.

Operation of the CRT terminals is functionally similar to those in the ACC. An exception is that the functions of page callup, cursor control, and command and data entry, which are accomplished by special keyboards in the ACC, are performed through a standard typewriter keyboard (alpha numeric/numeric) at the POCC.

Printers

Three printers are located behind the shift dispatcher's console. One printer is used to log alarms as they are received by the POCC computer; the second printer is used to log changes in status and to print out the dispatcher's log entries; and the third printer is an "off-line" device for project scheduling, rescheduling, and data logging. There are four additional printing devices, one located in each of the aqueduct ACCs. These are connected to the POCC computer through leased communications. Dispatchers can direct the same information to these printers that is printed out over the "off-line" POCC printer.

Communications

The POCC is provided with both voice and data communication capabilities.

Data Communications. Data communications to all of the aqueduct control areas are provided from the POCC. Modems, compatible with those used in the ACC, are provided for each data communications line (both primary and back-up). The receivers at the POCC are connected to the communication line at all times, monitoring data responses to the ACC interrogations from all areas simultaneously. The transmitters in the POCC are connected to the communication lines only when the POCC is providing control of an area.

The functions of the communications terminal equipment at the ACC are performed at the POCC by the communications equipment of the computer.

The Oroville ACC will be connected in the future to the POCC computer for data monitoring only (no control) by a slow-speed, 300-baud, communication line.

Other data communications exist between the POCC computer and the Pacific Gas and Electric (PG&E) dispatch center in San Francisco to exchange load data and power availability information. Additional data communications are planned with the U.S. Bureau of Reclamation (USBR) and other operating agencies.

Voice Communications. Voice communications also are provided in the POCC. The POCC is connected to each of the ACCs with a separate, automatic, ring-down line. It is also connected to all the aqueduct ACCs by a single, manual-ring, party-line arrangement which can be patched across at the ACCs to give the dispatcher voice access to any remote site on the Project via the voice maintenance line.

In addition, dedicated voice lines are provided to other agencies: USBR, PG&E, Southern California Edison Company, and Los Angeles Department of Water and Power.

Operational Capability

Operational capability of the POCC is determined by the software which has been developed for the POCC computer, consistent with limitations of the POCC equipment itself. Unlike other contracts for control systems designed by the Department, where the software was a specification requirement imposed on the contractors, the application software for the POCC computer was designed and programmed by department personnel. This was done because of the long time frame over which the POCC is being implemented and the many different systems with which the POCC must be compatible. Software for the POCC computer can be simply classified as "on-line" or "off-line". On-line software is that which is required for data monitoring (DISPATCH) and for back-up control (BACS) of the Project. Off-line software is run on the POCC computer but in a non-real-time environment.

DISPATCH Software. The normal mode of operation from the POCC is data acquisition and display. The POCC computer continuously receives data from each control area in response to interrogations issued from the ACCs. These data are validated and stored in main memory for use by other application programs.

Certain of these data are automatically directed to the wall display panel whenever the data is different from that which is currently displayed. Certain alarms, which are generated by the POCC computer by comparing incoming data against dispatcher-entered high and low limits, are also directed to the display panel. These limits are entered through the CRT system. By proper entry of these limits, the computer will "watch" certain key operating parameters in the Project for operating exceptions. Changes in plant unit status (I/S—in-service, S/D—shutdown, or O/S—out-of-service) are also directed to the display panel. The alarm conditions and changes in unit status are also transmitted to the alarm and events CRT and to the appropriate printer for a permanent record.

Data stored in main memory are also made available to the dispatchers on demand through various CRT devices. By calling appropriate CRT pages, the dispatcher is able to monitor the most recent data from any facility of the Project. Summary pages containing specially formatted data displays also are available.

Some of the data are used to compute operating parameters. Flows through the check structures are computed from the differential head across the gates and gate positions. Every three minutes, the project 30-minute integrated power demand is computed, projected to the end of the 30-minute demand period, and compared against the schedule. Deviations are alarmed to the dispatcher.

All of the data received by the POCC computer are recorded on magnetic tape for historical analysis purposes.

BACS Software. The POCC is provided with software to provide remote manual control of the facilities in any one aqueduct control area if, for any reason, its ACC is out of service. The POCC computer has been programmed with control software for each of the four aqueduct control areas. This software is normally stored in secondary storage. If the dispatcher desires control of an area, he can do so by manually initiating a BACS load for that area. From the point of initiation, the load and initialization of the BACS software is completely automatic. The POCC computer loads the appropriate BACS software from secondary storage. Concurrent with this, the jurisdiction control system sends a signal to the appropriate ACC equipment, causing the ACC modem transmitters to be disconnected from the communication line. The ACC computer is switched "off the line", and an acknowldgement is sent back to the POCC. Upon receipt of the acknowledgement, the POCC computer initializes the BACS software and notifies the dispatcher that the POCC is in control of the area. The system is interlocked so that the POCC can be in remote manual control of only one area at any given time. When BACS is in operation, DISPATCH is unaffected, i.e., BACS is in addition to, not in lieu of, normal DISPATCH operation.

For certain special conditions, the computer itself can automatically assume control of any or all of the aqueduct control areas. These special conditions result when operating conditions dictate the need for response times much shorter than the operators and dispatchers are capable of achieving. As an example, power supply contracts for interruptible on-peak power dictate automatic and instantaneous load dropping upon notification from the suppliers of certain operating conditions on their system. Within approximately one second after receipt of a load drop signal from the PG&E dispatch computer in San Francisco, the POCC computer immediately assumes control of all areas via the jurisdiction control system and sends emergency unit shutdown commands to the appropriate pumping units to reduce the total pumping load of the Project. Following this load drop, the POCC computer returns control back to the ACCs.

Off-Line Software. The POCC computer is provided with the capability to process programs in a "background" environment concurrent with operation of the DISPATCH and BACS software. This background or off-line software is related to the scheduling and rescheduling of project operation, data logging, and report generation.

Whereas the DISPATCH and BACS software have been predominantly written in assembly language, the off-line software has been written in FORTRAN. The Department's programming staff enhanced the vendor-supplied FORTRAN to provide FORTRAN programmers with the ability to access the real-time data base in main memory, communicate with the CRT system, communicate with the remote printers in the ACCs, and utilize the secondary storage devices as intermediate data storage files. This allows the use of practically all the POCC equipment for FORTRAN programs concurrent with the operation of DISPATCH and BACS software.

Jurisdiction Control System

Coordination of control from the POCC or the ACC to ensure that both are not attempting to control an area simultaneously is the function of the jurisdiction control system. If both centers were to attempt control at the same time, they would interfere with each other on the command-interrogation communication line to such an extent that coherent control or interrogation would be impossible and the control system would become inoperable.

The jurisdiction system was implemented to provide automatic means of preventing the control centers from interrogating or commanding the area simultaneously. In normal operation, system jurisdiction is controlled at the POCC, but means are provided to override jurisdiction at the ACC if the normal system fails.

Figure 45 is a functional block diagram of the jurisdiction system used at the POCC and each area control center. Using a single, full-duplex, voice grade communication line with a terminal at each control center, frequency-shift-keyed audio tones are used by the POCC to assign jurisdiction and by the ACCs to acknowledge jurisdiction. The audio tones are "frequency multiplexed", that is, each transmitted tone is within a band 120 hertz wide and a filter on each receiver rejects all signals outside of its band. Thus, the band for tone #7 is centered at 1,140 hertz (1,080 to 1,200 hertz), while tone #8 is centered at 1,260 hertz (1,200 to 1,320 hertz). Within its assigned band, each tone has three states: "Mark" at 30 hertz above center frequency, "idle" at center frequency, and "space" at 30 hertz below center frequency. The receivers, by use of filters, distinguish these states and vary their output to the computer accordingly.

In normal operation, the POCC assumes control of one or more areas by sending a "mark" over both tone transmitters to the ACC. The ACC acknowledges POCC control by returning a "mark" over both its transmitters. Area control center jurisdiction is similarly established by an exchange of "space" signals.

Emergency Power

Power to the equipment in the POCC will be provided by an uninterruptible power supply similar to that in the area control centers. Emergency power is presently being provided by a diesel engine-generator.

Design of Miscellaneous Facilities

In addition to the check structure, pumping and power plant control systems, ACCs and the POCC, other miscellaneous facilities have been provided with control capability as a part of the Project's control system design and construction activities.

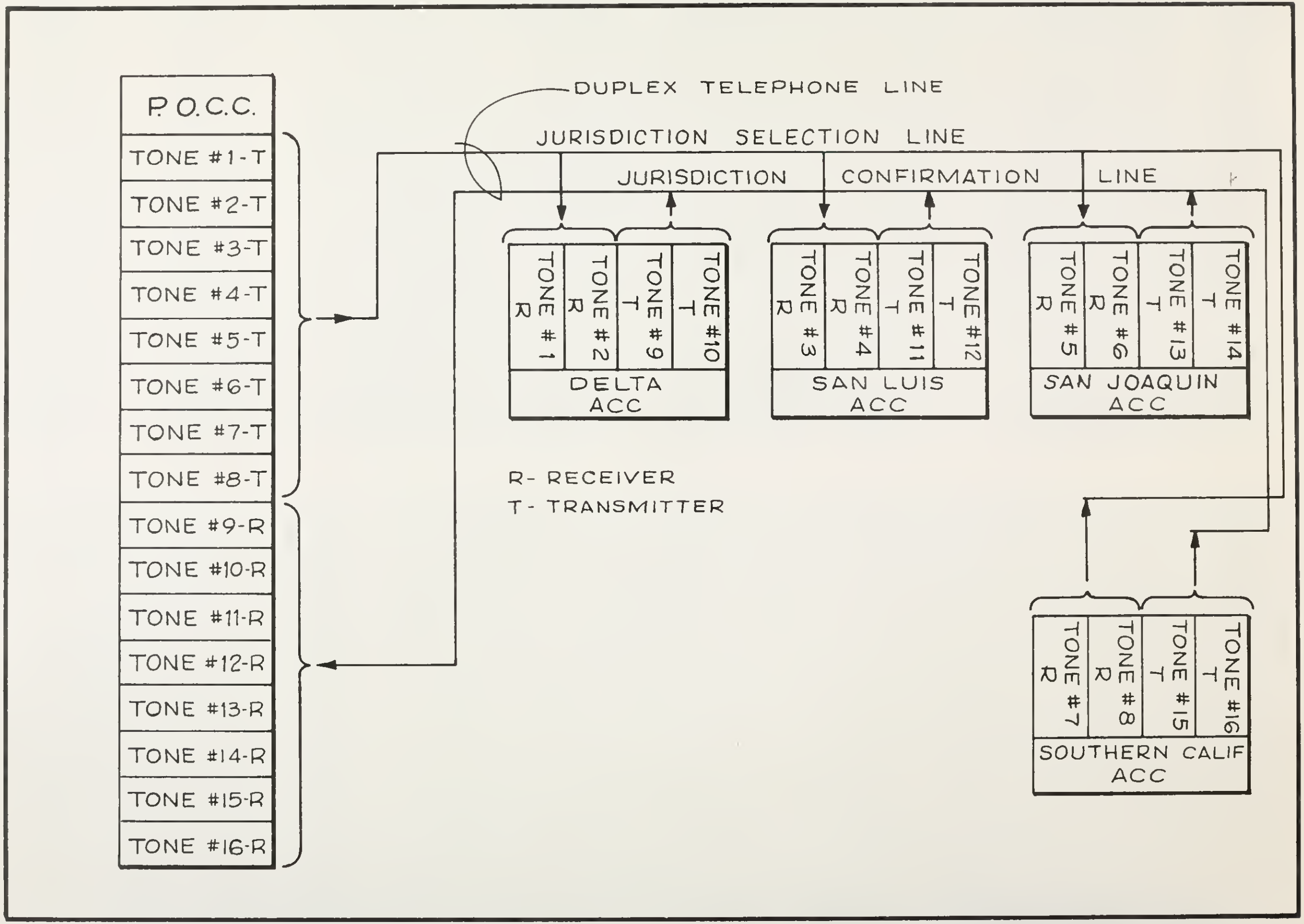


Figure 45. Functional Block Diagram—Jurisdiction Control System

Major miscellaneous systems include:

1. Turnout control system
2. Structural behavior instrumentation data acquisition system
3. Power demand monitor system

Another major system, a communication line continuity monitoring system, is discussed in Chapter VII, Communication Systems. In addition, minor miscellaneous systems have been provided.

Turnout Control System

A turnout is a structure for diversion of water from the Aqueduct to the Project's water users. These turnouts can be either gravity flow, pump flow, or a combination of pump-gravity flow.

All of the 43 turnouts in the San Joaquin control area will be equipped by 1975 with systems to allow for remote monitoring and control of these facilities from the San Joaquin ACC. To provide this remote capability, each turnout is being provided with a turnout control electronic assembly (TCA).

To avoid the complications created by increasing the number of termination points on aqueduct communication lines, turnout monitoring and controlling data will be relayed through nearby check structures as subordinate sites. Interrogations and commands from the ACC will be decoded by the check structure computer, reformatted, and transmitted directly to the turnout. Returning data, status, and alarms will be treated in a similar manner.

The TCA will perform the following functions at the turnout:

1. Scan at one-second intervals for all monitored data and store data for transmission when interrogated.
2. Operate up to four gates to cause gate position to match commanded setpoints.
3. When on automatic, adjust gate positions to cause flow to match commanded flow setpoint.
4. Convert analog inputs from sensors to scaled digital numbers.
5. Convert scaled digital number to analog output for flow controller setpoint.

The TCA will perform the following functions related to data handling to and from the check structure:

1. Receive, demodulate, check for validity, and decode commands and interrogations.
2. Encode; add parity and identification; modulate; and transmit data, status, and alarm messages.

The design of the TCA incorporates a microprocessor system to perform controlling and monitoring functions at the turnout and to provide communications with the check structure. This microprocessor system will be provided with both PROM (programmable read-only memory) for program storage and RAM (random access memory) for data storage.

Structural Behavior Instrumentation Data Acquisition System

To monitor the structural behavior of certain structures during seismic activity, the Department has installed Structural Behavior Instrumentation Data Acquisition System (SBIDAS) equipment at A. D. Edmonston, Pearblossom, and Wheeler Ridge Pumping Plants; Devil Canyon Powerplant; and Castaic Dam.

The purpose of this SBIDAS is to sample output signals from various types of transducers, convert these outputs to digital signals, and record these signals on magnetic tape for later analyses. The transducers monitored consist of triaxial accelerometers, pore pressure cells, concrete stress meters, and soil stress meters.

The SBIDAS starts operation by external detection of seismic activity greater than a predetermined threshold level. Within 50 milliseconds after the threshold value has been exceeded, the SBIDAS will begin to record data and continue to record for a minimum of four minutes, or until the seismic activity is reduced below the threshold level.

The SBIDAS consists of a mini-computer system, input signal conditioning networks, input multiplexing equipment, analog-to-digital conversion equipment, and a magnetic reel-to-reel recording device.

Procurement and installation of the SBIDAS were part of the A. D. Edmonston and Pearblossom Pumping Plant control system contracts.

Although the SBIDAS was designed as a part of the control system, it is not interfaced to the remote control system in any manner. It is a local device and is not used in the operation of the Project.

Power Demand Monitor System

Various sources of electric power are utilized to meet the pumping needs of the Project. The total pumping demand cannot exceed the total of power availability without creating an "extra capacity" demand on the supplier's system. This extra capacity results in heavy penalties if the demand is incurred during an on-peak period.

The official record of power demand for each of the pumping plants is recorded on magnetic tape recording equipment at each plant. These tapes are assembled monthly and time correlated, and projectwide demand for each 30-minute interval is computed. This occurs substantially after the extra capacity demand may have been created. To reduce the possibility that an extra capacity demand will be unknowingly incurred, the Project is operated with a 15-megawatt margin between scheduled power and actual demand. This margin represents an investment in scheduled but unused power. To reduce the margin, a power demand monitoring system is being implemented which will provide the dispatching personnel in the POCC with real-time, actual integrated demand information as it occurs.

This power demand monitoring system consists of instrumentation (demand monitors) on each of the recording demand meters at the plants. These demand monitors will be scanned every 15 seconds by the ACC from which the plant is controlled and the data will be transmitted to the POCC. From these data, the POCC computer will compute and display the Project's 30-minute integrated demand.

Miscellaneous Systems

Other miscellaneous systems have been designed as a part of the Project's control systems. These include systems for control and monitoring of reservoir intakes and outlets, pipelines, flowmeters, stream gauging stations, and other appurtenant features.

No attempt will be made here to completely describe all of the details of these various miscellaneous systems. Most of these systems are located in the Southern California control area. A complete description of the control and monitoring capability existing at each of these facilities can be found in Specification No. 71-01, "California Aqueduct Control System, Southern California Control Area".

CHAPTER VI. CONTROL SYSTEM CONSTRUCTION

All significant portions of the work to construct control systems for the Project were performed by contractors under provisions of the State Contract Act (Government Code Sections 14250–14427). Because of the requirement of this Act for competitive, fixed-price bidding, work progressed through the following steps:

1. Prequalification of prospective contractors.
2. Advertisement and award of the contract.
3. Administration of contracts and supervision of construction.

Prequalification of Prospective Contractors

The functional nature of all control system specifications made it imperative that prospective bidders be thoroughly screened for technical and financial capability prior to participation in the bidding process. A two-phase prequalification procedure for screening contractors was instituted to establish lists of qualified bidders whom the Department confidently believed could satisfactorily perform work if awarded to them.

In Phase I, a financial ability statement (Reference 7), a technical qualification questionnaire, and a two-page quality assurance program questionnaire (Reference 8) had to be completed by each prospective contractor. Only those contractors whose technical questionnaires and financial ability statements indicated that they had a potential capability of performing control system work of the complexity and magnitude required were allowed to enter Phase II of the prequalification procedure.

Phase II consisted of an inspection of the prospective contractor's facilities by the Department. The inspection team usually consisted of representatives of both the design and construction organizations. This team filled out an evaluation guide on each prospective contractor. The contractor was judged upon his capability of being the prime contractor and of being the actual contractor to perform the work on any or all of nine subsystems. The nine subsystems were:

1. Site equipment
2. Communication terminal equipment
3. Microwave equipment
4. Data collection equipment
5. Computer
6. Control consoles and displays
7. Recording instruments
8. Load-control equipment
9. Miscellaneous structural modifications

Advertisement and Award of Contracts

Construction work for each control system or part thereof was advertised as set forth in Article 3 of the State Contract Act. The "Notice to Contractors" (a document which generally described the requirements and extent of the work) in each case was sent to all prospective contractors whose prequalification indicated they were capable of performing the work. Only contractors who qualified as both prime contractor and as contractor for one or more subsystems were allowed to bid on major contract specifications. In many cases, the Department would designate a specific subsystem for which all bidding contractors must have been prequalified for performance of the construction work. This was done where a specific subsystem constituted a significant portion of the proposed work. For example, pumping plant control system contractors were required to be prequalified in the computer subsystem, and the contractor for the Project Operations Control Center wall display (Specification No. 70-12) had to be prequalified in the control consoles and displays subsystem.

Contracts were awarded to the contractor submitting the lowest responsible bid. Responsible bids were those for which all conditions of bidding stated in the bidding requirements were met and which were determined to be reasonable in cost in comparison with the engineer's estimate.

The actual bids for control system construction work were generally much lower than the State's estimates. The total of all bids for control system work was almost $10 million less than the $25 million estimated during the preliminary design phase. This fact probably can be attributed to the following factors:

1. A decline in aerospace industry workload at the time of advertisement for control system construction work. This resulted in highly competitive bidding by aerospace companies who were aggressively seeking a place in the industrial market.
2. Various contractors were much more familiar with essentially cost-plus federal contracting than with the provisions of the State Contract Act based on fixed-price bidding.
3. Decreasing costs in the 1960s of equipment utilized since preliminary estimates were made, because of advances in the electronic industry "state-of-the-art".

Administration of Contracts and Supervision of Construction

The Department's standard organization for supervision of construction activities consisted of Construction Project Offices at selected locations throughout the State. Each Project Office was staffed with the normal complement of construction inspectors experienced in civil, electrical, and mechanical work. A Project Office was responsible for all construction within a particular geographical area.

Electrical and mechanical items, such as turbines, pumps, motors, and related equipment, which required factory inspection and which were to be installed in aqueduct reaches or features within the Project Offices' areas of responsibility, were classified as special fixtures. These items were constructed under furnish and install contracts, administered under the State Contract Act. The furnish portion of the work (design, manufacturing, and factory testing) which took place at the contractor's facility for these contracts was supervised by department inspectors at the manufacturing facility under supervision of construction forces located in Sacramento. Supervision of the installation and field testing work was performed by construction forces of the appropriate Project Office.

Early Control System Construction Supervision

Initially, all control systems were considered to be in the category of special fixtures (factory inspection with field installation). Two contracts were completed under this concept of contract administration and construction supervision: the Delta Pumping Plant control system (Specification No. 65-41), and the interim alarm and level control system (Specification No. 67-32). Also, substantially all of the South Bay Model was completed in this manner.

In early 1968, however, technical difficulties arose on the South Bay Model which required technical expertise not available in the Project Office. This caused the Department to change the method of construction supervision for the remainder of the contract. A resident engineer headquartered in Sacramento, a specialist in control systems engineering, was assigned to provide technical supervision on site for the remaining work on the South Bay Model. Contract administration and overall responsibility for the contract, however, remained with the Project Office within its delegated authority until completion of the work.

In 1966, construction began on the Oroville-Thermalito control system (Specification No. 66-44). Initially, this system was treated as a special fixture. In late 1967, the design and factory test work for this contract had not yet been completed. All other construction activities for which the Oroville Project Office had responsibility were nearing completion. It was apparent that the control system contract would not be completed until after the date the Department had established for officially closing the Oroville Project Office.

As a result of this, in April 1968 the Department changed the method of construction supervision and contract administration of the Oroville-Thermalito control system to a method similar to that which had recently been established for completion of the South Bay Model. A control system engineer was assigned from Sacramento as resident engineer to supervise the balance of the construction work on the system. Unlike the South Bay Model, however, the resident engineer on the Oroville-Thermalito control system was provided with contract administration support from Sacramento headquarters contract administration staff. The resident engineer was assisted in field installation inspection and testing work by control system technicians on loan from the Oroville Field Division, Division of Operations and Maintenance.

Aqueduct Control System Construction Supervision

As a result of the experience associated with inspection of the South Bay Model as a special fixture, it was decided to employ a different method of construction supervision for the aqueduct control system contracts. The method used was the same method as had been employed to complete the Oroville-Thermalito control system. This method of construction supervision (control system task force as it came to be called) was used to supervise completion of all of the California Aqueduct control systems and most of the facilities in the Project Operations Control Center.

A resident engineer, a specialist in control system engineering, was assigned to each contract beginning with preparation of in-house designs and specifications. Personnel with experience in the inspection of electrical or other construction work were assigned to inspect the electrical and mechanical activities associated with the control system in the field. Personnel with control system experience were assigned as factory inspectors and to assist in field installation and checkout of the equipment. Other assistance to the resident engineer's task force was provided by personnel in other departmental units on a participant basis. Thus, the control system task force resident engineer was able to draw on various expertise available within the Department without concern for organizational constraints.

Several benefits of the task force concept were achieved over those of the Department's previous control system construction methods. First, by having electronic control system specialists instead of electrical inspectors perform the inspection work during the design, manufacturing, and testing phases of construction, many potential design and maintenance problems were averted. Secondly, the technician-inspectors were better trained for their ultimate duty of performing maintenance on the control system equipment. The involvement of technicians during the design, manufacturing, and factory testing work enabled them to obtain first-hand knowledge of the system design. Their early involvement also enabled them to obtain actual maintenance experience because their checkout testing work at the manufacturing facility was performed while the system was suffering from the initial failure stage of its component parts. Thirdly, the control system engineering staff who participated on the task force, but were not directly responsible for construction supervision, obtained first-hand knowledge of the system design for future use in providing engineering support to the operation and maintenance personnel. Finally, the task force staff was able to minimize potential misinterpretations of the specification during the design and manufacturing phases of the work because of their intimate knowledge of the Department's requirements and the intent of the specifications.

Plant Control System Construction Supervision

Initially, it was planned to supervise construction of the pumping plant control systems as special fixtures. Much of the factory inspection of these systems was accomplished in this manner. By early 1972, however, only one of the systems had been installed in the field. With the regular electrical-mechanical work, except for the control systems, near completion in the Project Offices at about that same time, the Department elected to complete the remaining factory inspection, field installation, and testing of the pumping plant control systems using the task force concept.

Transition to the task force concept was handled without difficulty. Control system personnel who were used as factory inspectors continued on the task force to lend continuity to the plant control system testing work.

Also, plant control system design engineers for several of the plant control systems provided technical supervision of some of the field testing work. This gave continuity to the engineering evaluation of the systems since the design engineers had performed review of all shop drawings, data, and materials during the design, manufacturing, factory testing, and installation phases of the work.

Adopting the task force concept for plants also provided some training of control system engineers and technicians for future engineering support of operation and maintenance.

Control System Construction Contracts

The project control system, other than the South Bay Model, was constructed under 12 separate contracts. The completion of additional work has been performed by direct procurements of equipment/materiels with installation under service agreements or by department maintenance personnel. Table 17 summarizes the major plant control system contracts, and Table 18 summarizes the major aqueduct control system contracts. Only those contracts in excess of $100,000 are listed.

Scope of the Oroville-Thermalito Control System Contract

Work performed under Specification No. 66-44 consisted of furnishing and installing the supervisory systems for Edward Hyatt and Thermalito Powerplants and for Oroville Switchyard; the alarm, events, and status change logging equipment; the automatic load control system; and three telemetry systems. Maintenance of the system during the operational availability demonstration period, as well as operation and maintenance manuals, were also provided. Training in programming, maintenance, and operation of the system was included in the contract work.

Scope of the Pumping Plant Control System Contracts

Work performed under Specification No. 65-41 (Delta Pumping Plant) included furnishing and installing the computer system, the operator's console, and the termination cabinets for the plant to the control system cabling. The uninterruptible power supply was also included. Preparation of maintenance manuals and training of department personnel in the programming, maintenance, and operation of the system were also included.

Work performed under Specifications Nos. 68-09 (Buena Vista and Wheeler Ridge Pumping Plants), 68-35 (Wind Gap Pumping Plant), 69-24 (A. D. Edmonston Pumping Plant), 68-05 (Oso Pumping Plant), and 71-02 (Pearblossom Pumping Plant) was essentially the same as at the Delta Pumping Plant except that the work included furnishing and installing the standard communications system

Table 17. Summary of Major Plant Control System Contract Data

	Delta	Oroville-Thermalito	Buena Vista and Wheeler Ridge	Wind Gap	Oso	A. D. Edmonston	Pearblossom
Specification	65-41	66-44	68-09	68-35	68-50	69-24	71-02
Low Bid Amount	$397,570	$1,247,500	$557,261	$458,898	$535,000	$889,000	$561,970
Final Contract Cost	$467,760	$2,137,501	$820,000 (Est)	$533,692	$601,438	$1,405,000 (Est)	$864,000 (Est)
Total Cost-Change Orders	$75,280	$983,554	$206,429*	$78,747	$85,113	$403,239*	$272,023*
Starting Date	12/22/65	10/17/66	6/20/68	2/27/69	2/20/69	4/27/70	5/20/71
Completion Date	2/10/70	5/18/72	12/74 (Est)	8/2/73	10/3/73	8/75 (Est)	6/75 (Est)
Prime Contractor	General Electric Co.	Philco-Ford	Rucker Co.	Litton Systems	Philco-Ford	Astrodata	Gulton Industries
Assignment 1	--				Litton Systems	Litton Systems	
Assignment 2	--	--			--	Gulton Industries	

* As of October 1974.

Table 18. Summary of Major Aqueduct Control System Contract Data

	Alarm and Level Control-Delta to 7th Std. Rd.	Delta to Buena Vista Pumping Plant and Coastal Branch	Buena Vista Pumping Plant to A. D. Edmonston Pumping Plant	POCC Wall Displays	So. Calif. Area
Specification	67-32	68-08	69-20	70-12	71-01
Low Bid Amount	$224,761	$1,983,000	$935,310	$173,900	$2,087,000
Final Contract Cost	$281,431	$2,519,090	$1,156,607	$187,279	$2,610,000 (Est)
Total Cost-Change Orders	$47,610	$419,486	$189,173	$6,604	$502,961*
Starting Date	6/8/67	5/8/68	12/24/69	7/9/70	4/19/71
Completion Date	9/14/68	10/14/71	4/30/72	1/20/72	12/74 (Est)
Prime Contractor	Meva Corp.	Fischbach & Moore, Inc.	Fischbach & Moore, Inc.	LFE Corp.	LFE Corp.

* As of October 1974.

(excluding the modems) required for interconnection to the ACC.

The SBIDAS (Structural Behavior Instrumentation Data Acquisition System) was also included as a part of Specifications Nos. 69-24 and 71-02.

Scope of the Aqueduct Control System Contracts

Work performed under Specification No. 67-32 (California Aqueduct Alarm Systems and Level Controls—Delta to 7th Standard Road) consisted of furnishing and installing analog water-level controllers and water-level sensing equipment at 26 check structures of the California Aqueduct and Coastal Branch Aqueduct, water-level sensing equipment at three pumping plants and one pump turnout, and alarm annunciator panels at the Delta ACC and the San Luis ACC.

Work performed under Specification No. 68-08 (California Aqueduct Control System—Delta to Buena Vista Pumping Plant) consisted of furnishing and installing the control system for that portion of the California Aqueduct from Clifton Court Forebay to Buena Vista Pumping Plant intake and the Coastal Branch Aqueduct.

This system enables the portion of the Aqueduct from Clifton Court Forebay to O'Neill Forebay to be monitored and controlled from the Delta ACC located at the Delta Operations and Maintenance Center. It provides equipment and cabling necessary for the Delta ACC and provides means to allow the control area to be remotely controlled from the POCC. Included in these controls are an acoustic velocity flowmeter and gate controls at Clifton Court Forebay, 12 check structure controls, the communications system for the Delta Pumping Plant control system, and electronic interfacing for two aqueduct acoustic velocity meters.

The San Luis control area originally started at O'Neill Forebay and continued to Buena Vista Pumping Plant intake and included the Coastal Branch Aqueduct. The control system in this reach provided all equipment and cabling required for remote control from the San Luis ACC, located at the San Luis Pumping-Generating Plant. Provisions to allow remote control of this area from the POCC were also included. (Subsequent to the completion of this contract, the Department modified the San Luis control area to end at Kettleman City. The facilities between Kettleman City and the Buena Vista Pumping Plant intake including the Coastal Branch are now controlled from the San Joaquin ACC.)

Included in the work in the San Luis control area was the furnishing and installing of control and instrumentation equipment at 18 check structures and two noncomputerized pumping plants (Las Perillas and Badger Hill), level instrumentation at San Luis Pumping-Generating Plant and Dos Amigos Pumping Plant, and interfacing for an aqueduct acoustic velocity meter.

Work also included the furnishing of system maintenance manuals, maintenance of the system while it was being tested, and training of department personnel.

Work performed under Specification No. 69-20 (California Aqueduct Control System—Buena Vista Pumping Plant through A. D. Edmonston Pumping Plant) consisted of furnishing and installing the control system for that portion of the California Aqueduct.

This system enables the Aqueduct to be monitored and controlled from the San Joaquin ACC located at the San Joaquin Operations and Maintenance Center near Bakersfield. Included in these controls are seven check structures and the modems for four pumping plant control systems.

The work also included the furnishing of system maintenance manuals, maintenance of the system while it was being tested, and training of department personnel.

Work performed under Specification No. 71-01 (California Aqueduct Control System—Southern California Area) consisted of furnishing and installing the control system for that portion of the California Aqueduct from A. D. Edmonston Pumping Plant surge tank to Lake Perris on the East Branch and to Castaic Lake on the West Branch.

The system enables the portion of the California Aqueduct included in the Southern California control area to be controlled from the Southern California ACC and also makes provisions to allow this area to be controlled from the POCC. At the area control center, located at the Castaic Operations and Maintenance Center, all equipment including an uninterruptible power supply and cabling were furnished and installed.

Also included in the work were the following items: furnishing and installing control equipment and cabling for 10 two-gate and 9 three-gate check structures; Quail inlet and Quail outlet structures; Gorman Creek inlet structure; Cottonwood chute gate; Tehachapi Crossing complex; Castaic, Cedar Springs, Pyramid, and Perris Dams and Reservoirs; electronic interfacing of Oso and Pearblossom Pumping Plants; Devil Canyon Afterbay complex; and Devil Canyon and Castaic Powerplant controls (see Appendix B for general location of these facilities).

Included in the work was furnishing system maintenance manuals, maintenance of the system while it was being tested, and training of department personnel.

Work performed under Specification No. 70-12 (Project Operations Control Center Wall Displays and Accessories) consisted of furnishing and installing all equipment and cabling to provide a wall display of the Project in the POCC located in the Resources Building, Sacramento. Included in the work was equipment required to implement the area control center jurisdiction system throughout the Project. Maintenance of the equipment and training of department personnel in maintenance and operation techniques were also included.

Complexity of Control System Fabrication and Installation

The fabrication and installation of the control system components under the various contracts was not without complications. These complications were technical and administrative in nature. Technical imperfections encountered on initial contracts prompted revisions in the specifications for later contracts. Whenever technical problems became apparent during contract performance, they were resolved either by contract change orders or by the work of departmental forces following completion of the contract.

A control system "Retrofit" program has been established for department personnel to perfect and integrate the individual control systems for optimum operational effectiveness. The purposes of the program are: (1) adjust each subsystem on-site (i.e., a plant control system in the plant control room) for operational reliability and acceptability, and (2) interconnect each subsystem for remote operation from the ACC or the POCC with comparable operational reliability and acceptability. Retrofit work requires from one to two years for completion on each contract. Because of the flexibility inherent in a computerized control system, the required adjustments can be accomplished mostly by software modifications with only a few hardware changes.

CHAPTER VII. COMMUNICATION SYSTEMS

The communication systems required for operation of the State Water Project are comprehensive and extensive. They can be broadly classified as data communications and voice communications. The various communication systems are used at all times, and the Project's operation is entirely dependent upon them. They are one of the most critical links in the project control system and require a high degree of reliability.

The entire complex of communications used in the control system are leased from a combine of telephone companies within California, with Pacific Telephone and Telegraph Company acting as spokesman for the industry. The mobile VHF radio system used in the general operation and maintenance of the Project is a state-owned system.

Planning of Communications

In 1963, communication requirements for the South Bay Aqueduct Control System Model began to finalize. The Department prepared preliminary designs and cost studies for a state-owned communications system to satisfy these requirements. At the same time, the Pacific Telephone and Telegraph Company prepared a proposal for furnishing the necessary circuits and facilities under a lease arrangement. A comparison of lease versus purchase was made, and the results indicated it was advantageous to utilize leased facilities for the Model study. Leasing would also serve as a test of this method for providing the communications necessary for the entire Project, based upon the Department's experience on the South Bay Model. Thus, an agreement for lease of South Bay communications was negotiated between the State and Pacific Telephone and Telegraph Company.

In early 1966, the Department determined that an independent opinion on the question of leased versus state-constructed communication facilities would be valuable in reaching a decision on furnishing communications for the entire Project. Various leading consulting firms in the field of communications were selected for appraisal by the Department. After evaluation, Messinger Consultants Company was selected to conduct the study.

The Company was requested to:

1. Investigate the total communication requirements of the Project which would include but not be restricted to voice, VHF mobile radio, teletype or other written messages, and telemetering and control links, along with any back-up facilities for any of these items, and submit a comprehensive plan outlining the total communication needs.

2. Investigate the alternative methods which might be used to meet these communication needs and recommend the one which should be implemented.

3. Investigate the communication personnel requirements for the Project and make a recommendation on the organization and staffing required to carry out the recommended plan and method of implementation selected.

4. Review and provide consulting service on design of the communication links as related to the State Water Project.

5. Assist in preparation of specifications for procurement of communication facilities of the Project as required.

The study took place during the period from July to December 1966, and a report was presented to the Department on January 15, 1967 (Reference 9). The Company recommended that the Department lease the necessary communication facilities for the State Water Project.

Following this recommendation, which was accepted by the Department, negotiations were begun for furnishing the necessary communications. Prior to these negotiations, Pacific Telephone and Telegraph Company met with all other private communication companies of the State whose territory the Project would pass through and obtained their authority to act for them in these negotiations. Participants in these negotiations included members from the Pacific Telephone and Telegraph Company, Department of General Services, and Department of Water Resources. Negotiations resulted in an agreement which made all necessary provisions for lease of data and voice communications for control of the Project.

Data Communications Design Requirements

Actual design and construction of the communications system was done by the telephone industry. The Department's role in this design was to develop the minimum requirements the system had to meet, including provisions for future expansion.

When remote control is exercised over a water delivery system as large and complex as the State Water Project, it is essential that it be available to perform its task at all times. Any downtime, scheduled or unscheduled, during which control points cannot be monitored or controlled, carries a very high risk of damage to the facilities and their surroundings, as well as a threat to the safety of personnel.

The communications system is the most vulnerable and one of the most essential links in the reliability chain. The vulnerability of the communication systems arises from their extended nature, which subjects them to failure and physical damage at places distant from department facilities. Their remoteness makes repair difficult and time consuming. Communication systems are also subject to the introduction of interfering noise from the atmosphere and adjacent electrical or communications equipment.

To ensure that communications would be reliable, the Department required high system availability of

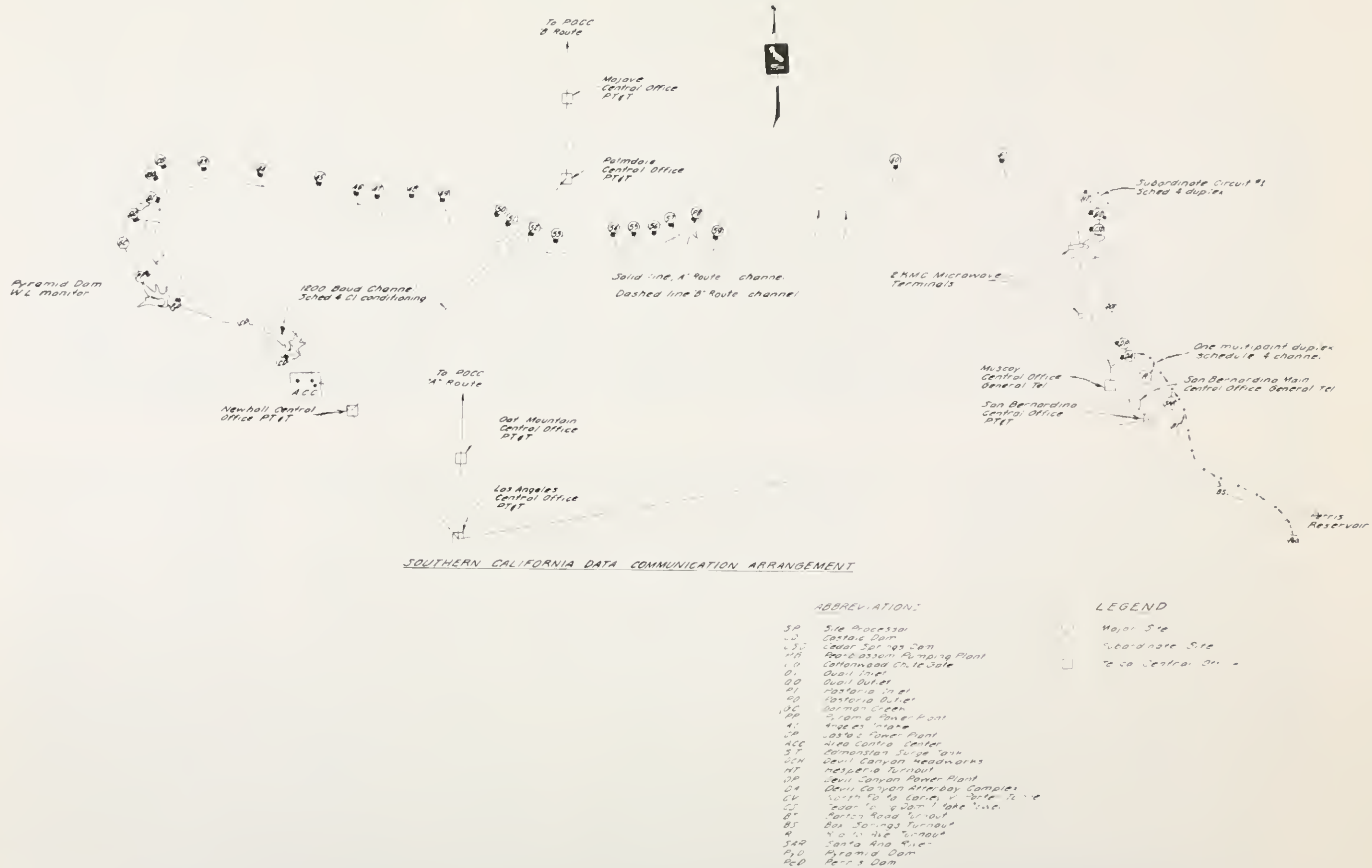


Figure 46. Typical Dual-Routed Communication Facility

service, extensive preoperational testing, early detection of failures to reduce the mean-time-to-repair, and special maintenance service. In addition, a right to interconnect department-owned communications was reserved in the event that this would enhance system reliability.

System Availability

The Department's requirements specified an availability of service, to any remote site, in excess of 99.95%. Dual routing of data communications is the principal measure to assure this high availability of communications. This is accomplished by providing two geographically separated routes from an ACC or the POCC to each of its dependent sites. Figure 46 shows diagrammatically the arrangement of a typical dual-routed data communication line. For simplicity, the diagram shows only the outgoing direction from the control centers to the remote sites; however, the lines are actually four-wire, full-duplex, and follow the same route in both directions.

Preoperational Testing

Preoperational testing required the telephone industry to perform extensive tests and evaluation of each communication line prior to acceptance by the Department. These tests were designed to ensure that any problems are discovered and corrected prior to the time the lines are put into service.

Early Detection of Failures

Communication failures can result from both department equipment failure and from communication line failures. It is important to be able to tell the difference promptly. Also, because of the telephone industries' commitment to provide a high degree of reliability, they insisted on prompt and automatic alarms when their lines perform improperly.

These imperatives resulted in an investment in equipment and computer programs to monitor the communication lines and sense communication failures rapidly, indicating where they are, both by location and by function in the system.

A communication line monitor is a system installed and operated by the Department. It consists of line monitor receivers at selected remote sites which close an output contact when digital signals are present at the point on the line to which they are attached. For any line segment, one line monitor is placed at the extreme sending end and one at the extreme receiving end. Thus, if the sending end reports messages being sent and the receiving end reports no messages being received, the conclusion is that the line has failed in between. These conditions are transmitted directly to the responsible telephone company as relay contact closures to terminals provided at each control center.

To interpret the line monitor output statuses, it is necessary to know other things about the status of the system: does the POCC or ACC have jurisdiction; has power failed momentarily or permanently at a telephone terminal; or is there evidence of failure of telephone cable or other telephone equipment at any location along the way.

To supply these data, the control system conveys to the appropriate control center and then to the telephone company's alarm system a power failure alarm and a "Telco" alarm from each remote site. The power failure alarm answers the question as to whether the loss of data was caused by a power failure between the sensing points. The "Telco" alarm discloses where there is or may be a failure of telephone equipment.

With this information, the responsible telephone company is able to dispatch a repair crew sooner and go to the right place, assuring prompt repair of failures and less probability of simultaneous failures on both communication routes.

Figure 47 is a block diagram of a typical line monitor system.

Special Maintenance Service

During negotiations with Pacific Telephone and Telegraph Company, the question arose regarding maintenance service of the circuits which would be provided to the Department. Since services would span the entire State and would be provided by many different companies, concern was expressed regarding how trouble calls would be directed to the proper maintenance organization. A Network Control Office, located at Pacific Telephone and Telegraph Company in Sacramento, was developed to serve as the receiving and clearing point for all trouble calls associated with project-leased circuits. This Network Control Office assumes the responsibility for directing the request for service to the proper telephone company repair group within the State on a 24-hour-per-day basis.

Interconnect of Parallel Circuits

By agreement, the Department reserved the right to build its own communication facilities to augment those of the carrier companies in the event that leased services were not able to be provided reliably or economically. As a part of the agreement, the State can construct its own circuits if another parallel circuit is leased. Because the leased services have been provided in a suitable and reliable manner, the Department has not utilized this right.

Voice Communications

To aid in maintenance of the extensive and complex project control systems, it was required that a voice communications system be provided which would make available an easy and convenient method of oral communications with other sites. At each site on the Project where significant amounts of electronic control equipment is located, a voice terminal,

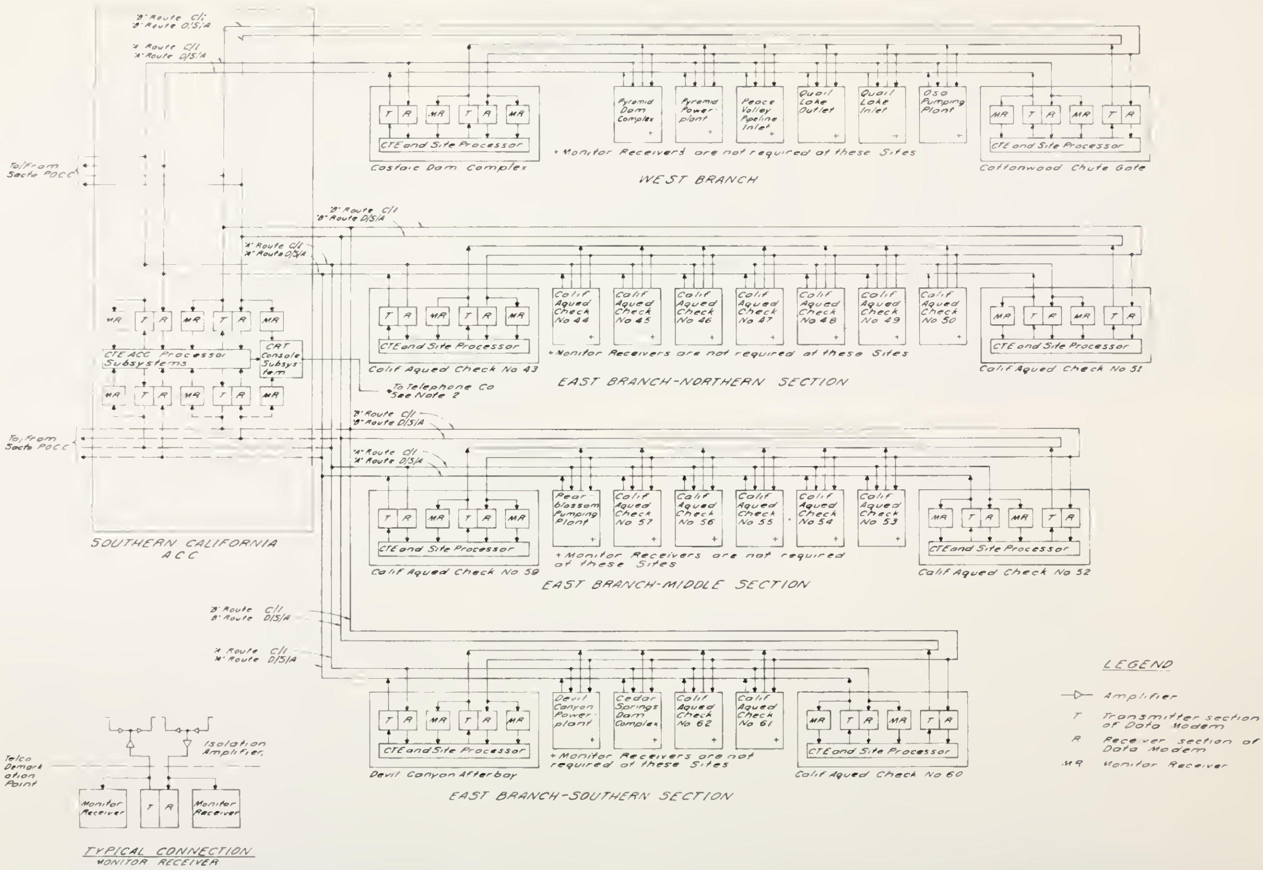


Figure 47. Functional Black Diagram—Typical Line Monitor System

complete with speaker and head set, has been provided. The circuit is arranged in a party-line manner. This allows two or more of the sites to be connected to one another simultaneously. This feature is used for the coordination required between sites during testing and maintenance of the control system.

Since these systems became operational, the voice communication circuits have been widely used as operational and security features of the Project, even more than originally anticipated. Other sites, where significant amounts of electronic equipment do not exist, also have been added to these systems.

Voice circuits which are used strictly for operational traffic also have been provided. These are dedicated circuits between the POCC and each ACC and between the POCC and various outside agencies.

APPENDIX A

REFERENCES

APPENDIX A

Selected List of References

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(2) __________, "Leased, Real-Time Computer System for the South Bay Aqueduct", September 1965.

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(5) United States Bureau of Reclamation, "Control and Graphic Boards for San Luis Pumping-Generating Plant", Invitation No. DS-6235, 1965.

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(7) State of California, "Contractor's Statement of Experience and Financial Conditions".

(8) California Department of Water Resources, "Confidential Questionnaire to Accompany and Become a Part of Contractor's Statement of Experience and Financial Condition".

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APPENDIX B

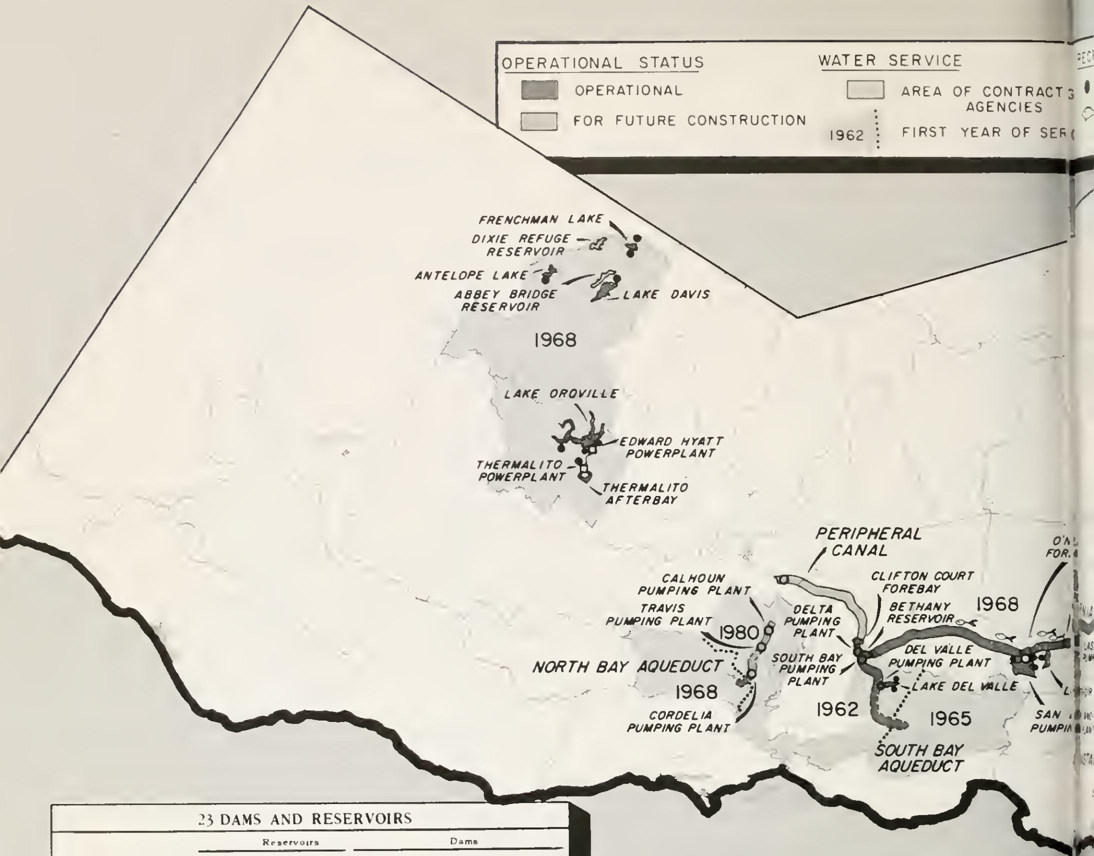
ENGLISH TO METRIC CONVERSIONS

AND PROJECT STATISTICS

CONVERSION FACTORS

English to Metric System of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches	2.54	centimeters
	feet	30.48	centimeters
		0.3048	meters
		0.0003048	kilometers
	yards	0.9144	meters
	miles	1,609.3	meters
		1.6093	kilometers
Area	square inches	6.4516	square centimeters
	square feet	929.03	square centimeters
	square yards	0.83613	square meters
	acres	0.40469	hectares
		4,046.9	square meters
		0.0040469	square kilometers
	square miles	2.5898	square kilometers
Volume	gallons	3,785.4	cubic centimeters
		0.0037854	cubic meters
		3.7854	liters
	acre-feet	1,233.5	cubic meters
		1,233,500.0	liters
	cubic inches	16.387	cubic centimeters
	cubic feet	0.028317	cubic meters
	cubic yards	0.76455	cubic meters
		764.55	liters
Velocity	feet per second	0.3048	meters per second
	miles per hour	1.6093	kilometers per hour
Discharge	cubic feet per second or second-feet	0.028317	cubic meters per second
Weight	pounds	0.45359	kilograms
	tons (2,000 pounds)	0.90718	tons (metric)
Power	horsepower	0.7460	kilowatts



23 DAMS AND RESERVOIRS

Name of Reservoir	Reservoirs: Gross Capacity(1 (Acre-feet)	Surface Area (acres)	Shoreline (miles)	Dams: Structural Height (feet)	Crest Elevation(2 (feet)	Crest Length (feet)	Volume (cubic yards)
Frenchman Lake	55,477	1,580	21	139	5,607	720	537,000
Antelope Lake	22,566	931	15	120	5,025	1,320	380,000
Lake Davis	84,371	4,026	32	132	5,785	800	253,000
Abbey Bridge	45,000	1,950	21	117	[illegible]	1,150	500,000
Dixie Refuge	16,000	900	15	100	5,754	1,050	400,000
Lake Oroville	3,537,577	15,805	167	770	922	6 920	80,000,000
Thermalito Diversion Pool	13,328	323	10	143	233	1 300	154 000
Fish Barrier Pool	580	52	1	91	181	600	10,500
Thermalito Forebay	11 768	630	10	91	231	15 900	1 840,000
Thermalito Afterbay	57,041	4 302	26	39	142	42,000	5,020,000
Clifton Court Forebay	28,653	2,109	8	30	14	36,500	2 440,000
Bethany	4,804	161	6	121	250	3 940	1 400,000
Lake Del Valle	77,106	1,060	16	235	773	880	4 150,000
San Luis	2,038,771	12,700	65	385	554	18 600	77 645,000
O'Neill Forebay	56,426	2,700	12	88	233	14 350	3 000,000
Los Banos	34 562	623	12	167	384	1,370	2,100,000
Little Panoche	13,236	354	10	152	676	1 440	1,210,000
Buttes	21,800	580	6	190	2,790	2,230	3,130,000
Silverwood Lake	74,970	976	13	249	3,378	2,230	7,600,000
Lake Perris	131 452	2,318	10	128	1,600	11,600	20,000,000
Pyramid Lake	171,196	1,297	21	400	2,606	1,090	6,860,000
Elderberry Forebay	28,231	460	7	200	1,550	1,990	6,000,000
Castaic Lake	323,702	2,235	29	425	1 535	4 900	46,000,000
Totals	6,848,617	58,072	533			172,880	270,629,500

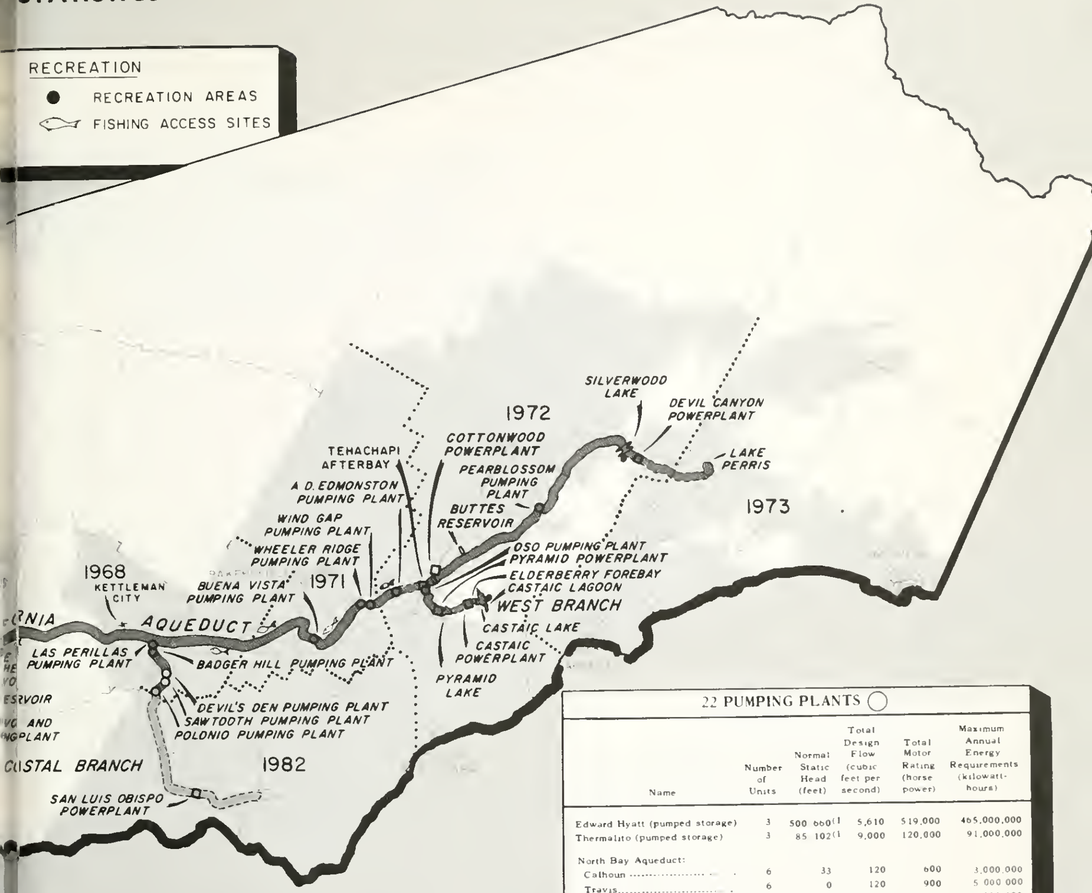
1) At maximum normal operating level

2) Above sea level.

AQUEDUCTS

Name	Length (miles): Total	Canal	Pipeline	Tunnel	Channel and Reservoir
North Bay Aqueduct	26.5	14 3	12 2	0	0
South Bay Aqueduct	42 9	8 4	32.9	1 6	0
Peripheral Canal	43.0	42 0	1 0	0	0
Subtotal	112.4	64 7	46 1	1.6	0
California Aqueduct (main line):					
Delta to O'Neill Forebay	68 4	67 0	0	0	1 4
O'Neill Forebay to Kettleman City	105.7	103 5	0	0	2 2
Kettleman City to A. D. Edmonston Pumping Plant	120 9	120.9	0	0	0
A. D. Edmonston Pumping Plant thru Tehachapi Afterbay	10 6	0 2	2.5	7 9	0
Tehachapi Afterbay thru Lake Perris	138 4	93 4	38 3	3 8	2 9
Subtotal, main line	444.0	385 0	40 8	11 7	6 5
California Aqueduct (branches):					
West Branch	31.9	9.1	6 4	7.2	9 2
Coastal Branch	96 2	14 8	81 4	0	0
Subtotal, branches	128.1	23 9	87 8	7 2	9 2
Totals	684.5	473 6	174 7	20 5	15 7

STATISTICS



8 POWERPLANTS

Name	Number of Units	Normal Static Head (feet)	Total Design Flow (cubic feet per second)	Power Generator Output (kilowatts)	Maximum Annual Energy Output (kilowatt-hours)
Edward Hyatt	6	410 676[1]	14,550	678,750	2,475,000,000
Thermalito	4	85 100[1]	16,900	119 600	383,000,000
San Luis					
Total	8	99 327[1]	13 120	424 000	
State Share			6,872	222 100	170,000,000
Cottonwood	1	140	1 637	15 000	115 000 000
Devil Canyon	2	1 418	1 200	119 700	1 003,000,000
Pyramid	2	740	3,100	157,000	1 001 000,000
Castaic					
Total	7	1,063	18 400	1,250,000	
State Share[2]			3 092	214,000	1,457,000,000
San Luis Obispo	1	730	111	5,900	41,000,000
Total, State Share					6,645 000,000

1) Minimum and maximum static heads

2) The City of Los Angeles Department of Water and Power will construct and operate a 1,250,000-kilowatt Castaic Powerplant and will supply the Project with electrical power and energy equivalent to the generation from a 213 984 kilowatt powerplant the State originally planned to construct

22 PUMPING PLANTS

Name	Number of Units	Normal Static Head (feet)	Total Design Flow (cubic feet per second)	Total Motor Rating (horse power)	Maximum Annual Energy Requirements (kilowatt-hours)
Edward Hyatt (pumped storage)	3	500 660[1]	5,610	519,000	465,000,000
Thermalito (pumped storage)	3	85 102[1]	9,000	120,000	91,000,000
North Bay Aqueduct:					
Calhoun	6	33	120	600	3,000,000
Travis	6	0	120	900	5 000 000
Cordelia	3	448	48	3,100	14 000,000
South Bay Aqueduct:					
South Bay	9	545	330	27,750	166,000,000
Del Valle	4	0 38[2]	120	1,000	2,000 000
California Aqueduct (main line):					
Delta	11	244	10,303	333,000	1,355,000,000
San Luis					
Total	8	99 327[2]	11,000	504,000	
State Share			5,762	264,000	313,000,000
Dos Amigos					
Total	6	113	13,200	240,000	
State Share			7 100	130,000	607,000,000
Buena Vista	10[3]	205	5,049	136,000	746,000,000
Wheeler Ridge	9[3]	233	4,598	140,000	797,000,000
Wind Gap	9[3]	518	4,410	308,000	1 761,000,000
A. D. Edmonston	14[3]	1,926	4 095	1,040,000	5,916,000,000
Pearblossom	6	540	1,380	113,200	647,000,000
California Aqueduct (branches):					
Oso	8	231	3,128	93 800	446,000,000
Las Perillas	6	55	450	4,050	20,000,000
Badger Hill	6	151	450	10,500	56,000,000
Devil's Den	4	409	126	8,000	51,000,000
Sawtooth	4	331	126	6,500	41,000,000
Polonio	4	810	126	16,000	101,000,000
Peripheral Canal					
Total	9[3]	10	21 800	35 200	
State Share			10,900	17 440	88,000 000
Total, State Share					13,691,000,000

1) Minimum and maximum total pumping heads

2) Minimum and maximum static heads

3) Includes one spare unit.

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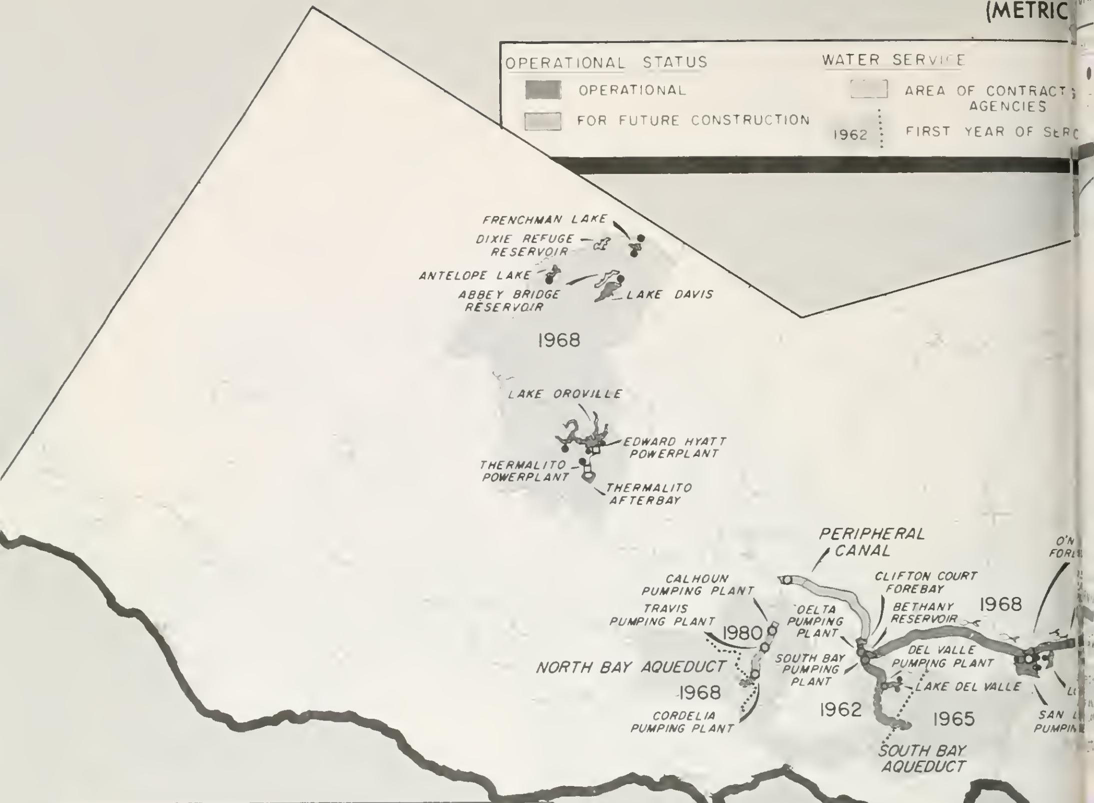


23 DAMS AND RESERVOIRS

Name of Reservoir	Reservoirs: Gross Capacity[1] (millions of cubic meters)	Reservoirs: Surface Area (hectares)	Reservoirs: Shoreline (kilometers)	Reservoirs: Structural Height (meters)	Dams: Crest Elevation[2] (meters)	Dams: Crest Length (meters)	Dams: Volume (cubic meters)
Frenchman Lake	68.43	639	33.8	42	1709	219	410,600
Antelope Lake	27.84	377	24.1	37	1532	402	290,500
Lake Davis	104.07	1,629	51.5	40	1763	244	193,400
Abbey Bridge	55.51	789	33.8	36	1669	351	382,300
Dixie Refuge	19.74	364	24.1	30	1754	320	305,800
Lake Oroville	4,363 60	6,396	268.8	235	281	2,109	61,164,000
Thermalito Diversion Pool	16 44	131	16 1	44	71	396	117 700
Fish Barrier Pool	0 72	21	1.6	28	55	183	8,000
Thermalito Forebay	14.52	255	16.1	28	70	4,846	1,406,800
Thermalito Afterbay	70.36	1,741	41.8	12	43	12,802	3,838,000
Clifton Court Forebay	35 34	853	12.9	9	4	11,125	1,865,500
Bethany	5.93	65	9.7	37	76	1,201	1,070,300
Lake Del Valle	95 11	429	25.8	72	236	268	3,172,900
San Luis	2,514.82	5,140	104.6	117	169	5,669	59,363,500
O'Neill Forebay	69.60	1,093	19.3	27	71	4,374	2,293,700
Los Banos	42 63	252	19 3	51	117	418	1 605 600
Little Panoche	16 33	143	16 1	46	206	439	925 100
Buttes	26.89	235	9.7	58	850	680	2,393,000
Silverwood Lake	92.48	395	20.9	76	1,030	680	5,810,600
Lake Perris	162 15	938	16 1	39	488	3 536	15,291,000
Pyramid Lake	211 17	525	33 8	122	794	332	5,244,800
Elderberry Forebay	34 82	186	11 3	61	472	607	4,587,300
Castaic Lake	399 29	904	46.7	130	468	1,494	35,169,300
Totals	8,447 79	23,500	857.9			52,695	206,909,700

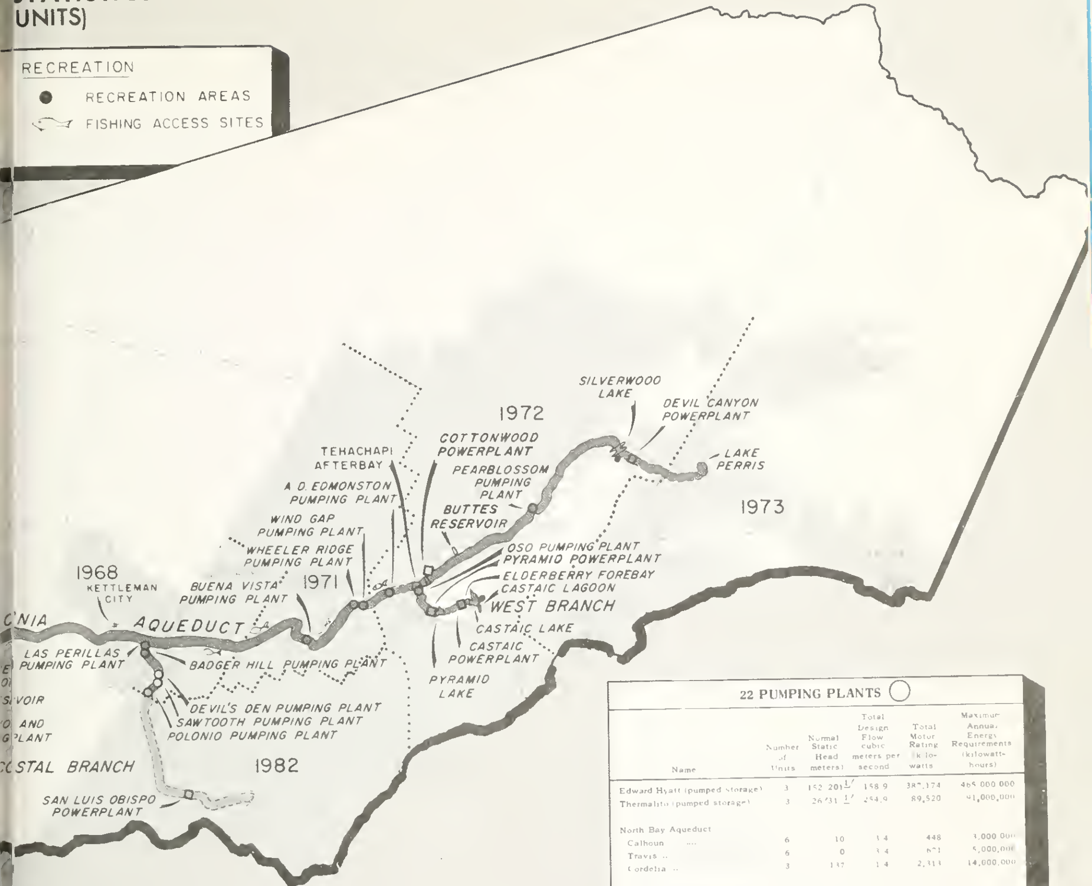
1/ At maximum normal operating level.

2/ Above sea level.

AQUEDUCTS

Name	Length (kilometers): Total	Canal	Pipeline	Tunnel	Channel and Reservoir
North Bay Aqueduct	42 6	23 0	19 6	0	0
South Bay Aqueduct	69 1	13 5	53.0	2.6	0
Peripheral Canal	69.2	67 6	1 6	0	0
Subtotal	180.9	104.1	74.2	2.6	0
California Aqueduct (main line):					
Delta to O'Neill Forebay	110.1	107.8	0	0	2.3
O'Neill Forebay to Kettleman City	170 1	166.6	0	0	3 5
Kettleman City to A.D Edmonston Pumping Plant	194 6	194 6	0	0	0
A D Edmonston Pumping Plant thru Tehachapi Afterbay	17 0	0 3	4 0	12 7	0
Tehachapi Afterbay thru Lake Perris	222 7	150 3	61 6	6 1	4 7
Subtotal, main line	714 5	619 6	65 6	18 8	10 5
California Aqueduct (branches)					
West Branch	51.3	14.6	10.3	11.6	14 8
Coastal Branch	154.8	23.8	131.0	0	0
Subtotal, branches	206 1	38 4	141.3	11 6	14 8
TOTALS	1 101 5	762 1	281 1	33 0	25 3

STATISTICS
UNITS)



8 POWERPLANTS

Name	Number of Units	Normal Static Head (meters)	Total Design Flow (cubic meters per second)	Power Generator Output (kilowatts)	Maximum Annual Energy Requirements (kilowatt-hours)
Edward Hyatt	6	125/206 1/	412.0	678,750	2,475,000,000
Thermalito	4	26/30 1/	478.6	119,600	383,000,000
San Luis					
Total	8	30/100 1/	371.6	424,000	
State Share			194.6	222,100	170,000,000
Cottonwood	1	43	46.4	15,000	115,000,000
Devil Canyon	2	432	34.0	119,700	1,003,000,000
Pyramid	2	226	87.8	157,000	1,001,000,000
Castaic					
Total	7	324	521.0	1,250,000	
State Share 2/			87.6	214,000	1,457,000,000
San Luis Obispo	1	223	3.1	5,900	41,000,000
Total, State Share					6,645,000,000

1/ Minimum and maximum static heads.

2/ The City of Los Angeles Department of Water and Power will construct and operate a 1,250,000-kilowatt Castaic Powerplant and will supply the Project with electrical power and energy equivalent to the generation from a 213,984-kilowatt powerplant the State originally planned to construct.

22 PUMPING PLANTS

Name	Number of Units	Normal Static Head (meters)	Total Design Flow (cubic meters per second)	Total Motor Rating (kilowatts)	Maximum Annual Energy Requirements (kilowatt-hours)
Edward Hyatt (pumped storage)	3	152/201 1/	158.9	387,174	465,000,000
Thermalito (pumped storage)	3	26/31 1/	254.9	89,520	91,000,000
North Bay Aqueduct					
Calhoun	6	10	3.4	448	3,000,000
Travis	6	0	3.4	671	5,000,000
Cordelia	3	137	1.4	2,313	14,000,000
South Bay Aqueduct					
South Bay	9	166	9.3	20,702	166,000,000
Del Valle	4	0/12 2/	3.4	746	2,000,000
California Aqueduct (main line)					
Delta	11	74	291.8	248,418	1,355,000,000
San Luis					
Total	8	30/100 2/	311.5	375,984	
State Share			163.2	196,944	313,000,000
Dos Amigos					
Total	6	34	373.8	179,040	
State Share			201.1	96,980	607,000,000
Buena Vista	10 3/	62	143.0	101,456	746,000,000
Wheeler Ridge	9 3/	71	130.2	104,440	797,000,000
Wind Gap	9 3/	158	124.9	229,768	1,761,000,000
A. D. Edmonston	14 3/	587	116.0	775,840	5,916,000,000
Pearblossom	6	165	39.1	84,447	647,000,000
California Aqueduct (branches)					
Oso	8	70	88.6	69,975	446,000,000
Las Perillas	6	17	12.7	3,021	20,000,000
Badger Hill	6	46	12.7	7,81	56,000,000
Devil's Den	4	125	3.6	5,968	51,000,000
Sawtooth	4	101	3.6	4,849	41,000,000
Polonio	4	247	3.6	11,936	101,000,000
Peripheral Canal					
Total	9	1	617.3	26,259	
State Share			308.7	13,010	88,000,000
Total, State Share					13,691,000,000

1/ Minimum and maximum total pumping heads.

2/ Minimum and maximum static heads.

3/ Includes one spare unit.